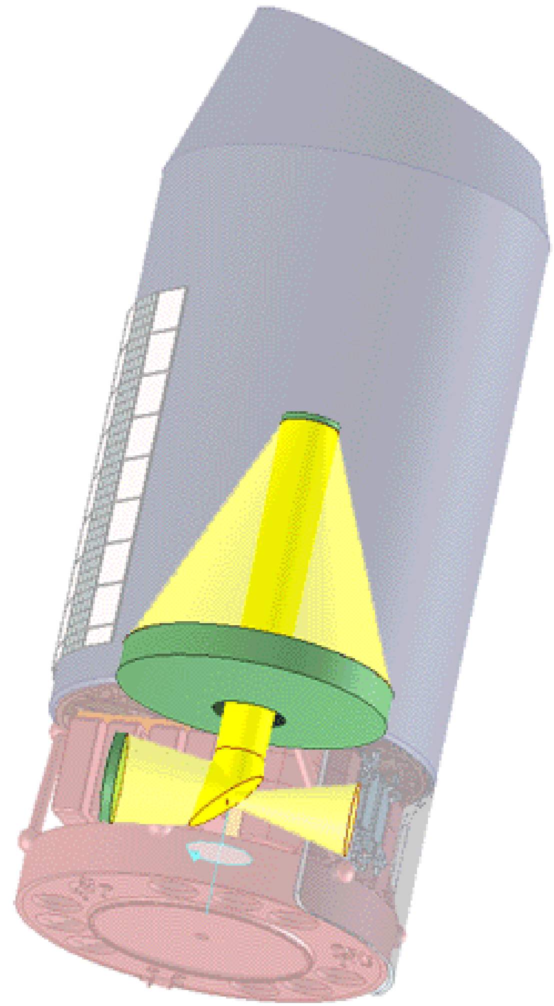
Understanding Dark Energy with the SuperNova Acceleration Probe (SNAP)



BNL
June 28th, 2006

Matt Brown
University of Michigan

Understanding Dark Energy with the SuperNova Acceleration Probe (SNAP)

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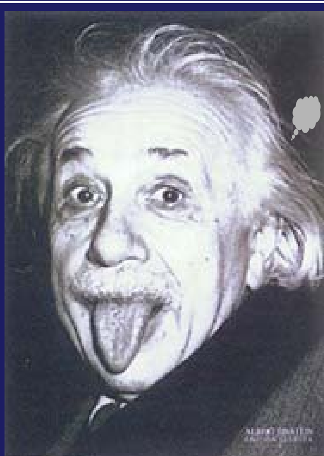
- Dark Energy & The Accelerating Universe
- The Observational Tool: SNe Ia
- SuperNova / Acceleration Probe (SNAP)
- NIR Instrumentation
- Science Reach

The Cosmological Constant

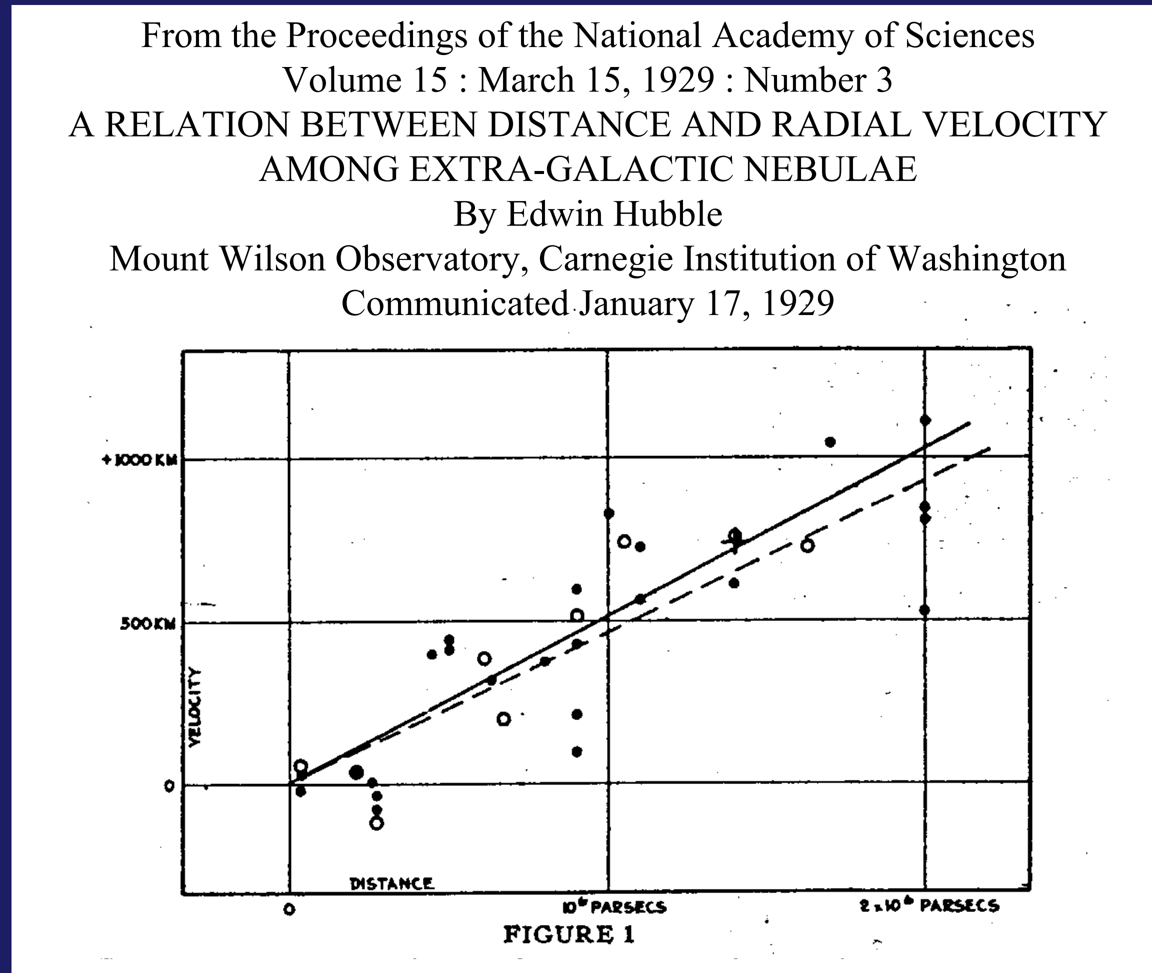


$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}$$

- In 1917 Einstein put a cosmological constant (Vacuum Energy) into his equations of General Relativity to allow for a static universe.
  - — Constant energy density
- By tuning the current value of Λ, attractive gravity due to matter density (and vacuum energy density) and the repulsive effect of the negative pressure can be made to just balance.
- Danger! Runaway solution if Λ is large and positive!

Hubble’s Law

Edwin Hubble
1889 – 1953



From the Proceedings of the National Academy of Sciences
Volume 15 : March 15, 1929 : Number 3
A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE
By Edwin Hubble
Mount Wilson Observatory, Carnegie Institution of Washington
Communicated January 17, 1929

FIGURE 1

Hubble combined his knowledge of galaxy redshifts with an estimate of the distance to these galaxies: The more distant a galaxy, the faster the galaxy ‘moves away’ from us: $v = H_o D$

Fundamental Questions

- What is the nature of matter and energy at its most fundamental level?

  (What is the universe made of?)

- What is the evolution and destiny of the universe and how is it affected by the fundamental interactions of energy, matter, time and space?

  (Is the universe infinite? Will it last forever?)

Destiny

Traditional philosophy of General Relativity (in absence of a cosmological constant): Geometry $\Rightarrow$ Destiny

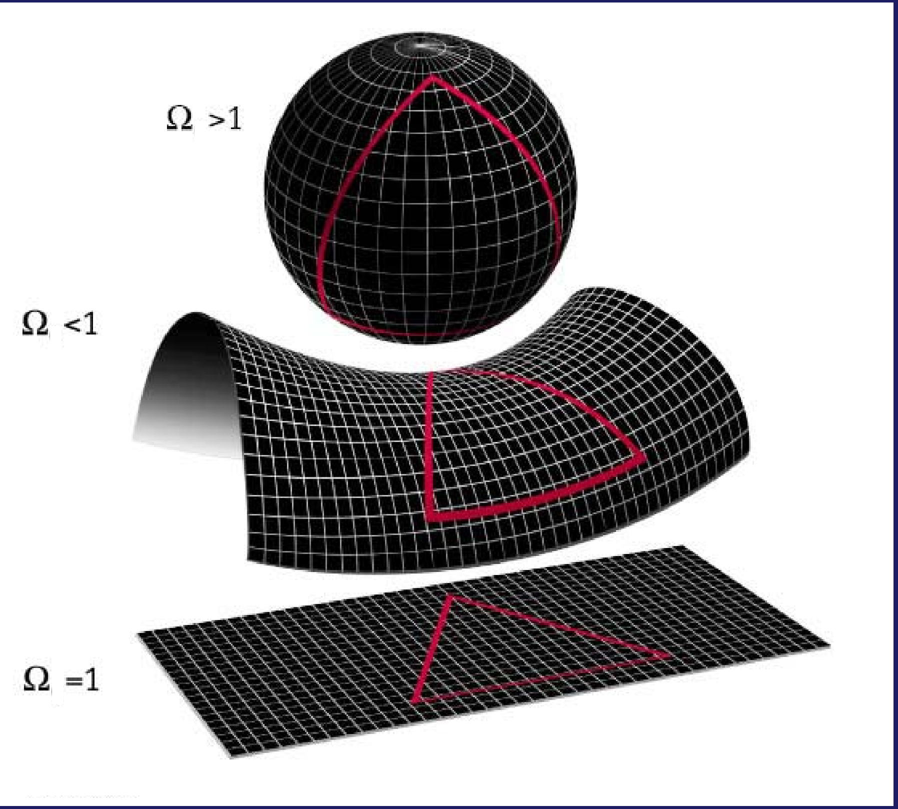
Geometry determined by the density parameter $\Omega \equiv \dfrac{\rho_{TOT}}{\rho_{crit}}$

$$\rho_{crit} \equiv \frac{3H_0^2}{8\pi G} = 1.9h^2 \times 10^{-29}\, g/cm^3$$

$\Omega > 1$ Positively curved space
$\Rightarrow$ Closed universe will eventually recollapse.

$\Omega < 1$ Negatively curved space
$\Rightarrow$ Open universe will expand forever.

$\Omega = 1$ No curvature
$\Rightarrow$ Flat universe expands asymptotically to rest.

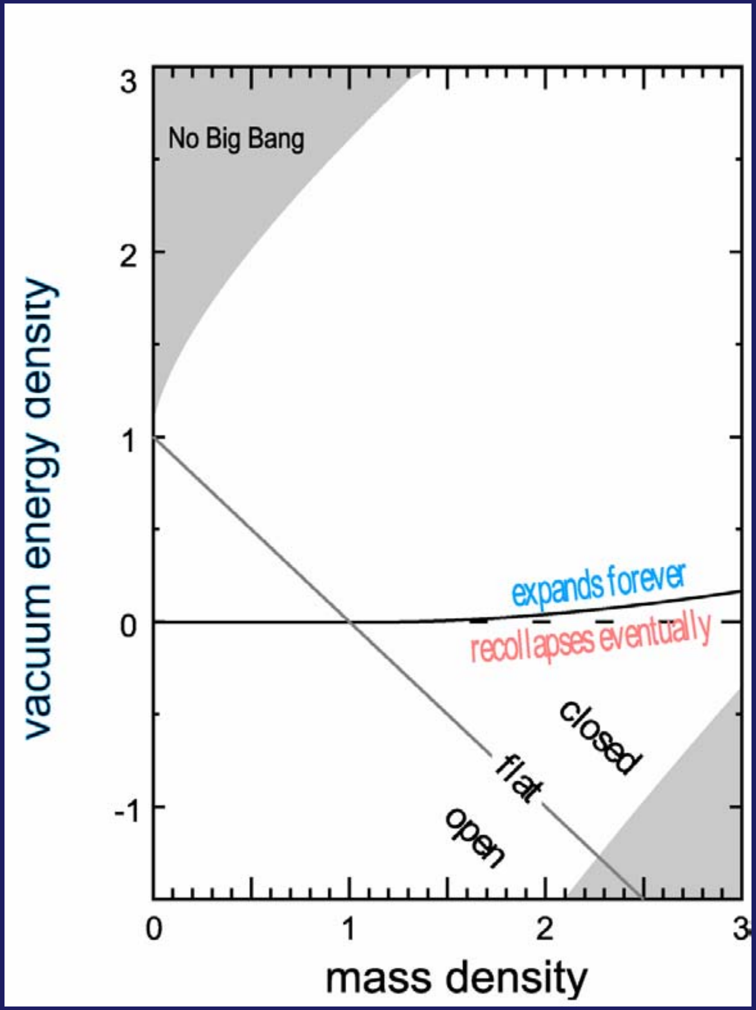


Dynamics of $\Omega = \Omega_M + \Omega_\Lambda$ Universes

Geometry $\Rightarrow$ Destiny …
Only true for a universe made entirely of “stuff” that dilutes with expansion (e.g. matter with ρ, $p > 0$)

Vacuum energy does not change as the universe expands; this implies increase in total energy ($p < 0$) accelerating the expansion of the universe.

Ω_Λ

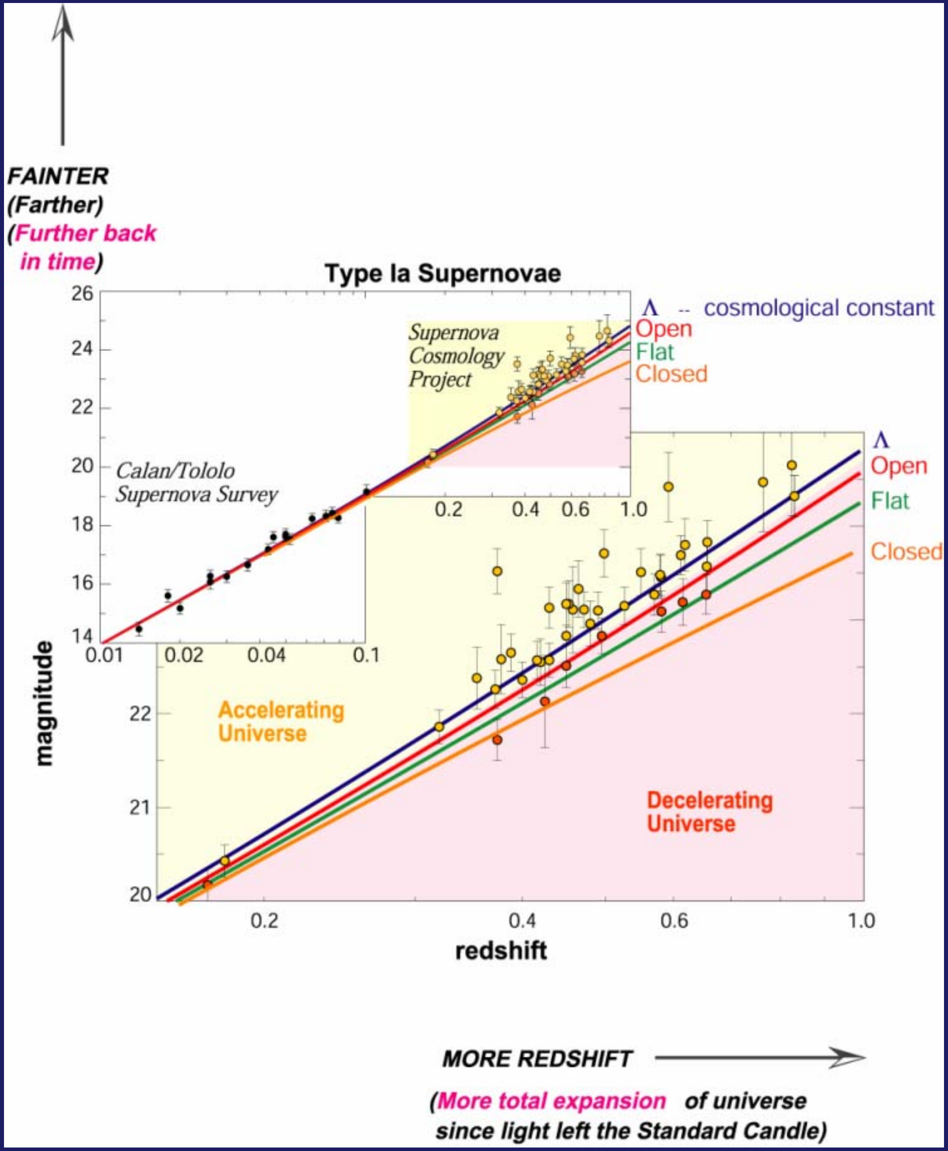


Ω_M

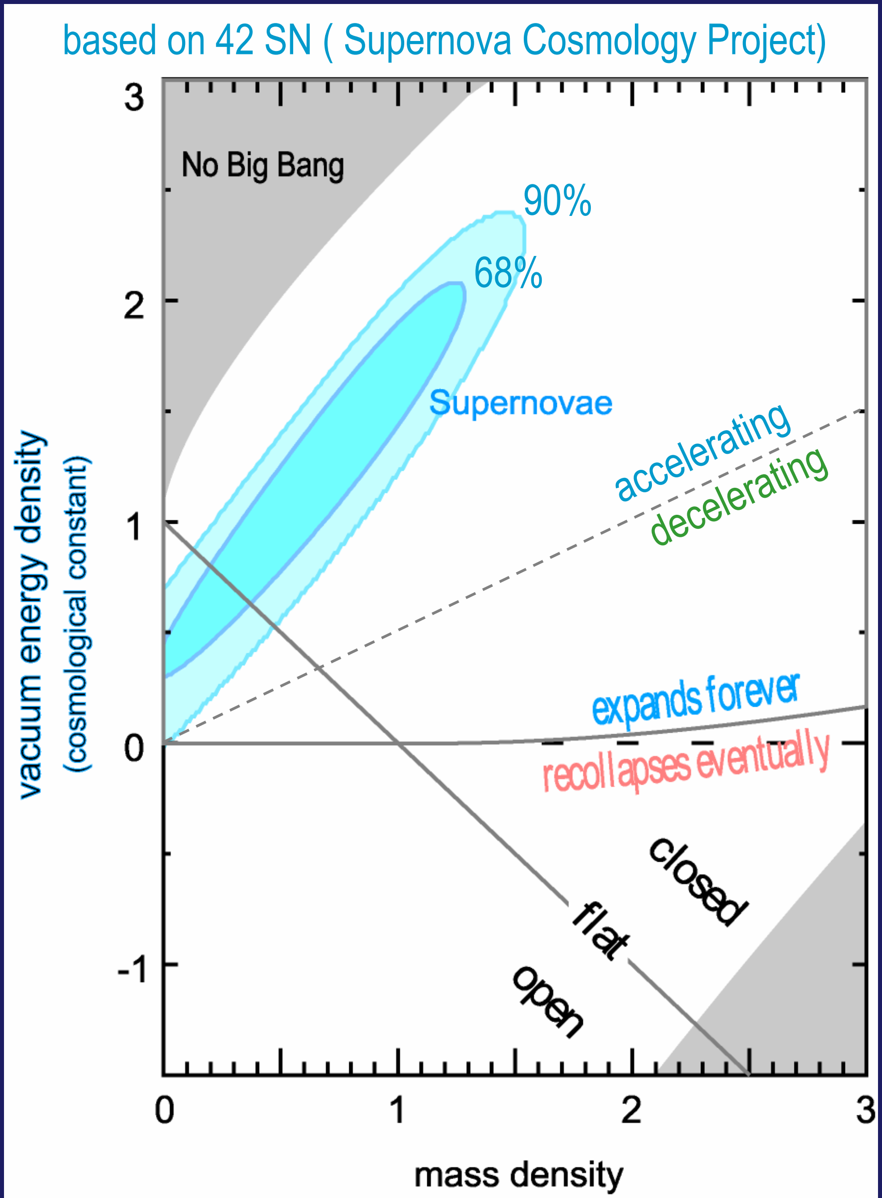
A Startling Discovery

Using type Ia supernovae the Supernova Cosmology Project and the High-Z Supernova team constructed a Hubble diagram out to z = 1.

Both teams made the startling discovery that the expansion of the universe is accelerating.

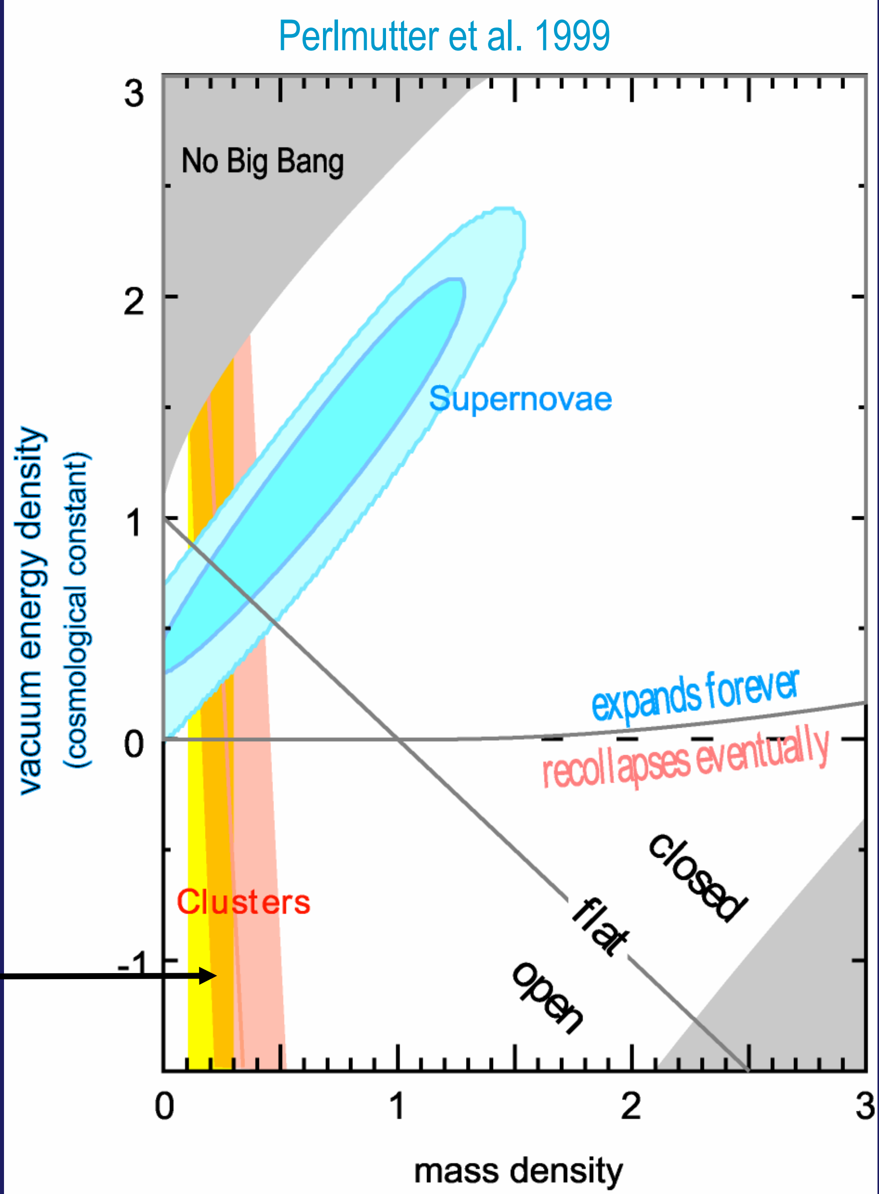


A Revolution in Cosmology



Constraints in the Ω_M–Ω_Λ plane as measured by the Supernova Cosmology Project.

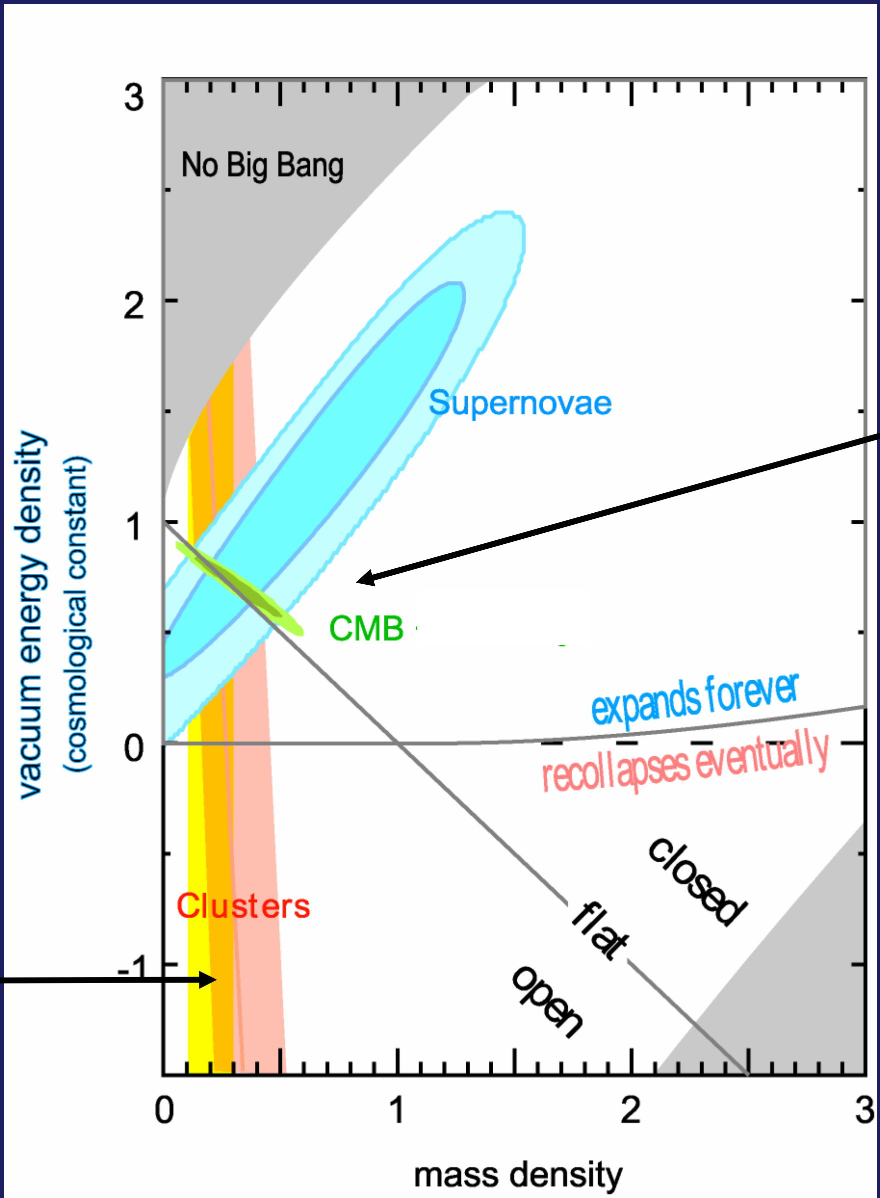
A Revolution in Cosmology

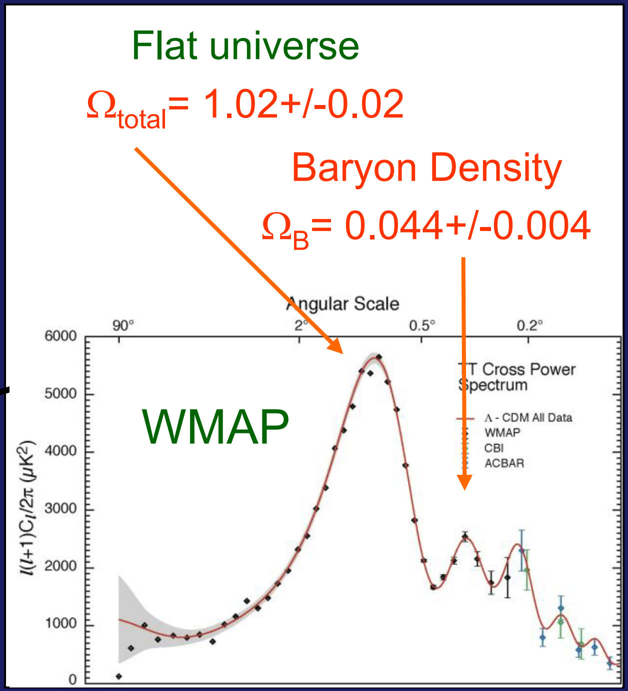


- Weak lensing mass census
- Large scale structure measurements

$\Omega_M = 0.3$

A Revolution in Cosmology



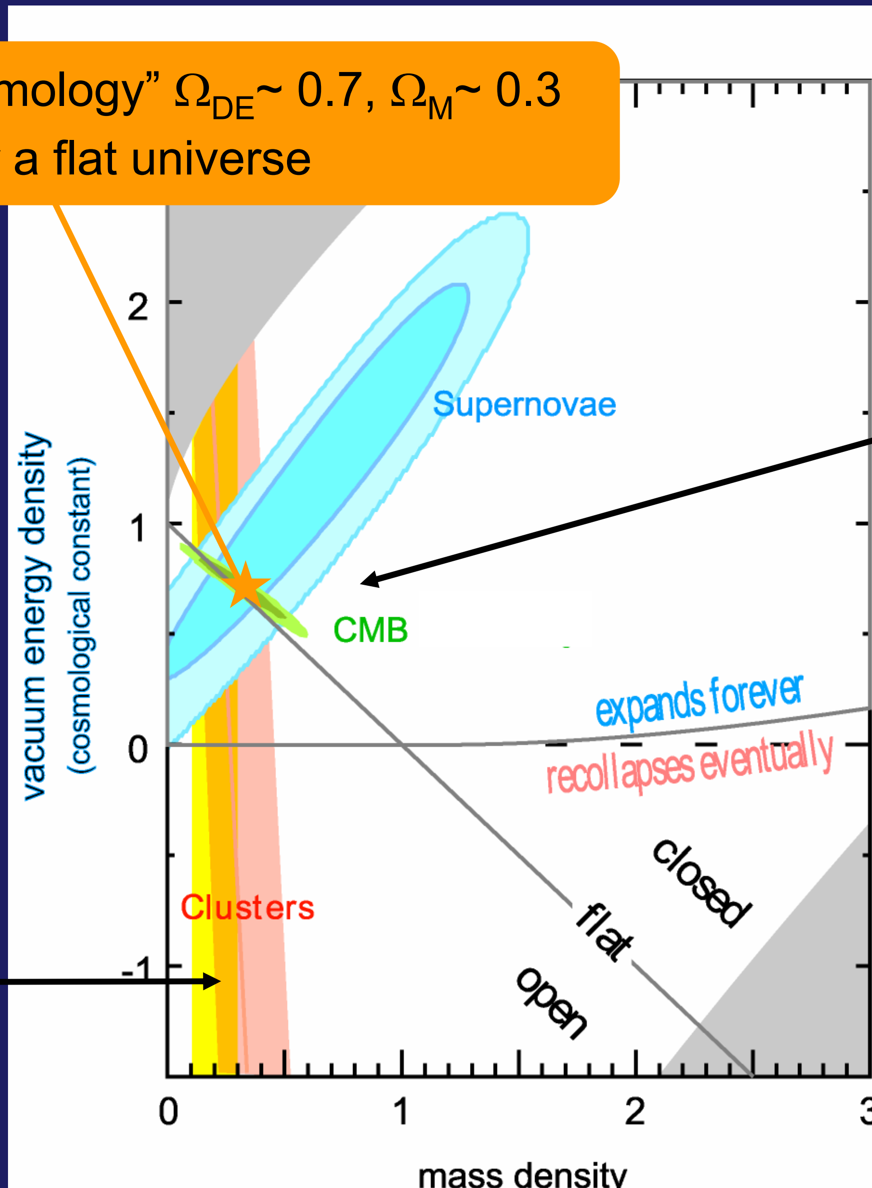


- Weak lensing mass census
- Large scale structure measurements

Ω_M= 0.3

A Revolution in Cosmology

"Standard Cosmology" Ω_{DE}~ 0.7, Ω_M~ 0.3
for a flat universe

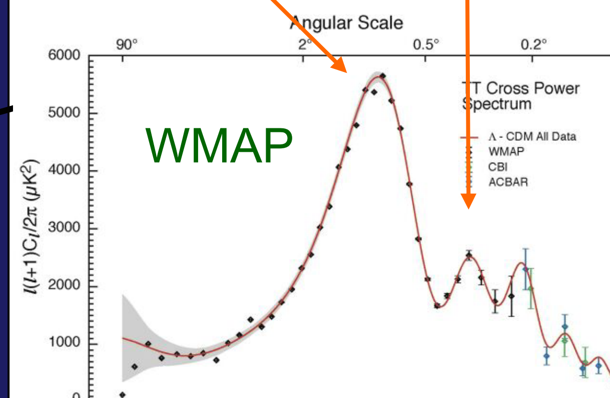


Flat universe

Ω_{total}= 1.02+/-0.02

Baryon Density

Ω_B= 0.044+/-0.004



- Weak lensing mass census
- Large scale structure measurements

Ω_M= 0.3

Energy Budget of the Universe

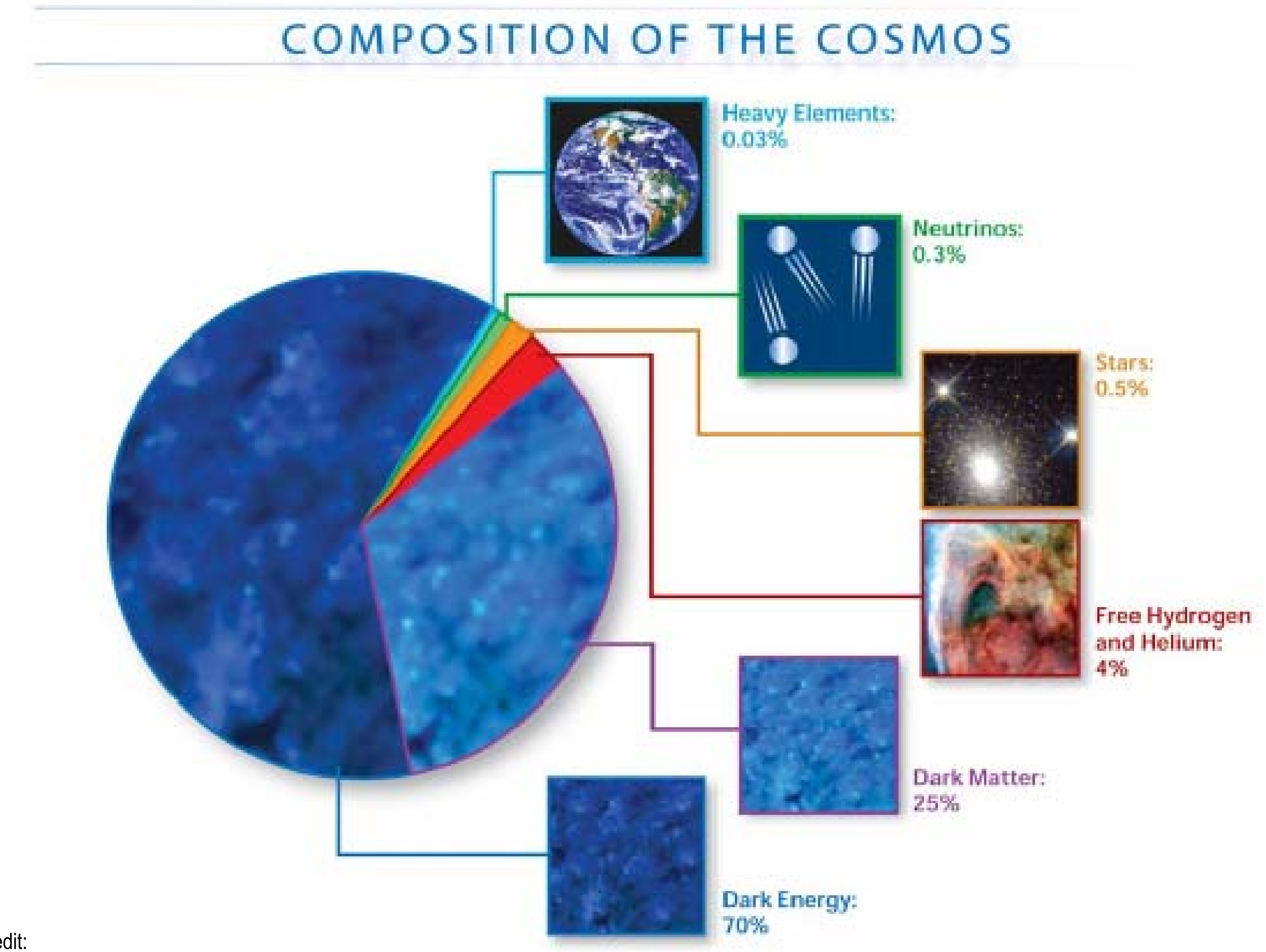


Illustration credit:
Ann Field, STScI

What is the nature of dark energy?

We now know that dark energy exists

- The dominant component of our universe
- Dark energy does not fit in current physics theory
- New theories propose a number of alternative physics explanations, each with different expansion history we can measure.

Two theories of dark energy:

- Cosmological constant or vacuum energy, constant over time
- Dynamical scalar field → “Quintessence”

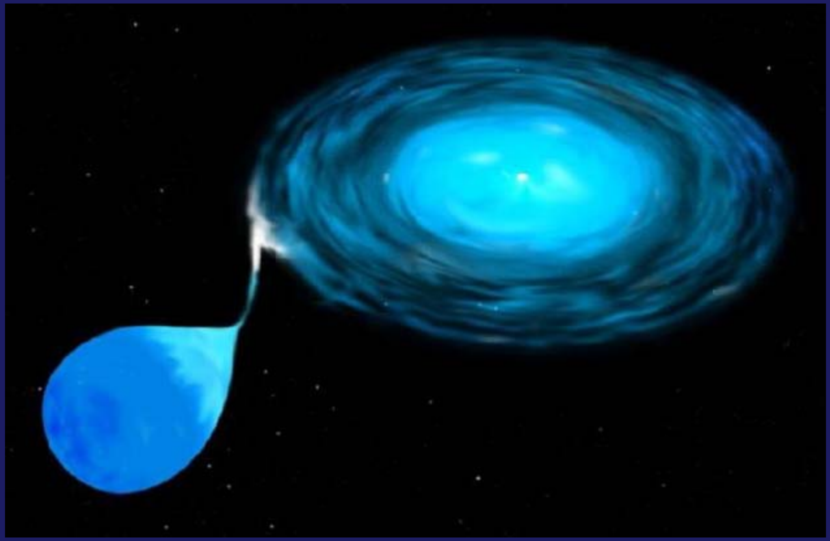
The Observational Tool: SNe Ia

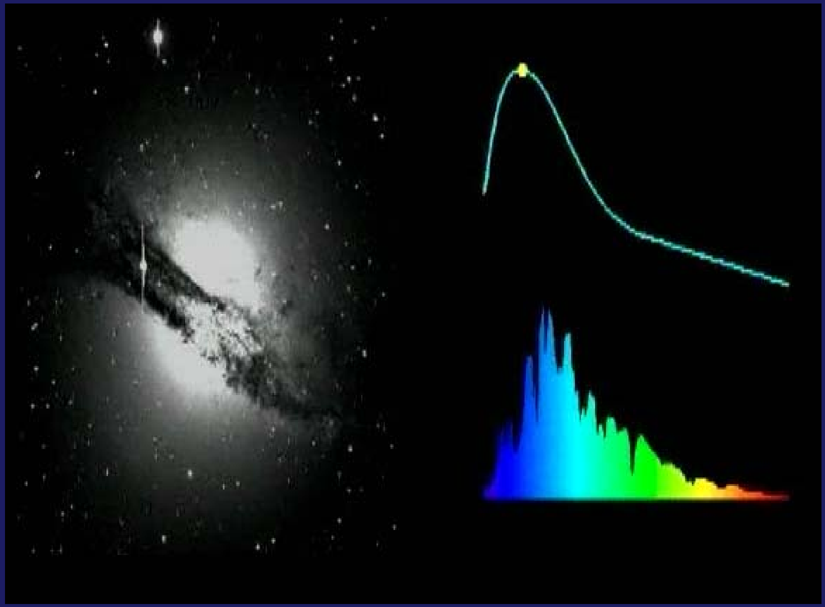
C/O white dwarf accretes mass of a companion star leading to a thermonuclear explosion near the Chandrasekhar limit (1.4 $M_{\odot}$)

- Explosion follows consistent pattern with nearly the same peak intensity
- Extremely bright event – observable on cosmological distance scales

- Spectrum and brightness evolve with time
- Peak Magnitude is a 'standard candle' to measure distance

$$Flux \propto \frac{1}{d^2}$$



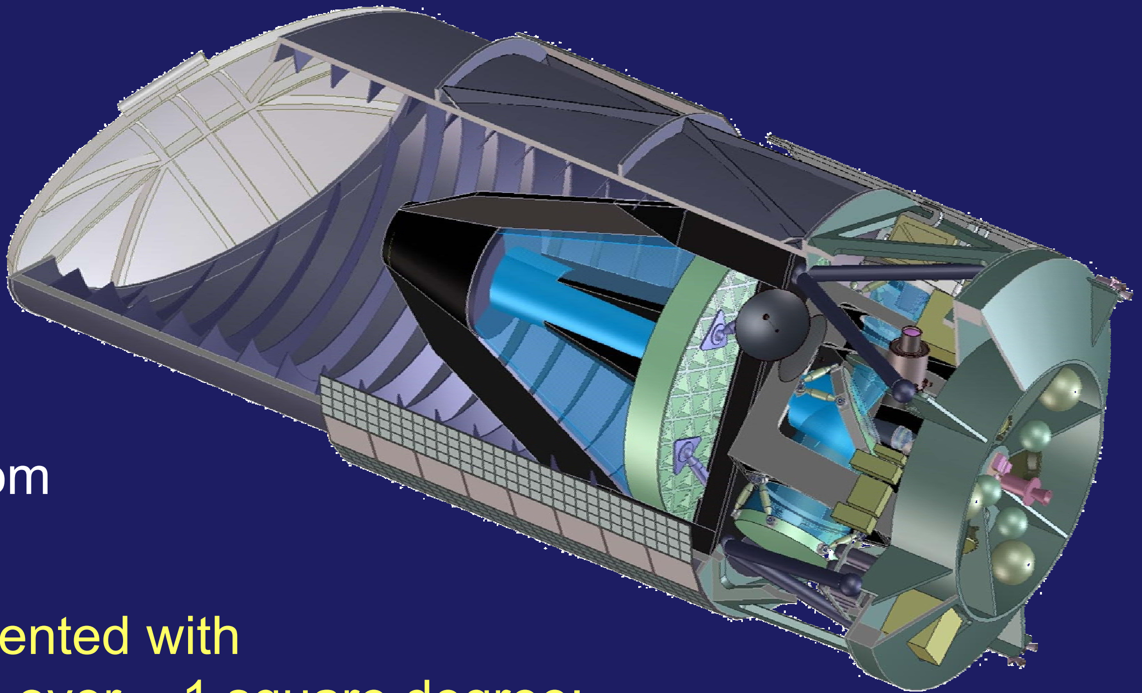


The SNAP Satellite

It’s a SNAP!

A ‘simple’ dedicated experiment to study the dark energy

- Essentially no moving parts



- 2 meter aperture telescope:
  sensitive to light from distant SN
- focal plane instrumented with > 600 million pixels over ~ 1 square degree:
  efficiently measures large number of supernovae
- Integral field optical and IR spectroscopy 350 – 1700nm:
  detailed analysis of each SN

The SNAP Collaboration

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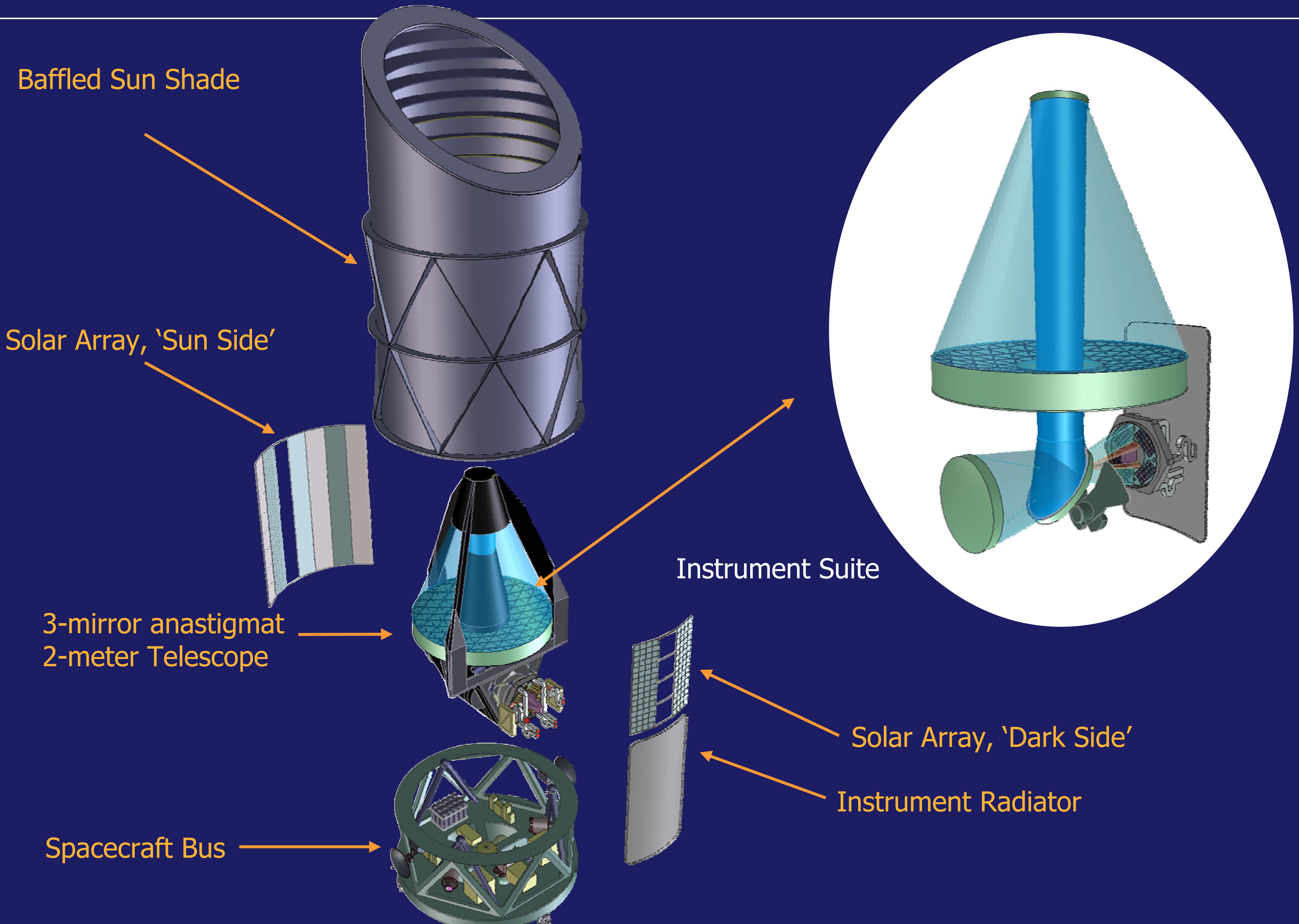
SLAC / Stanford	W. Althouse, R. Blandford, W. Craig, S. Kahn, M. Huffer, P. Marshall
STScI	R. Bohlin, A. Fruchter
Yale University	C. Baltay, W. Emmet, J. Snyder, A. Szymkowiak, D. Rabinowitz, N. Morgan

[†]Institutional affiliation

Instrument Concept

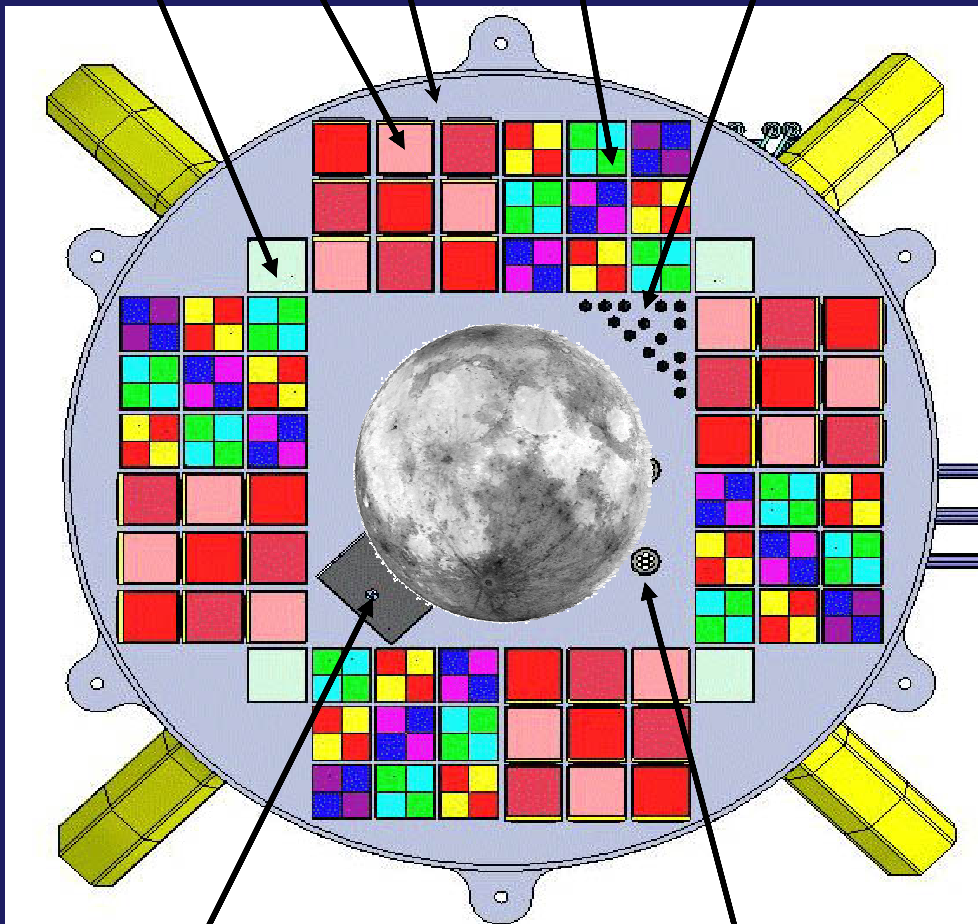


Focal plane

D=56.6 cm (13.0 mrad)

0.7 square degrees!

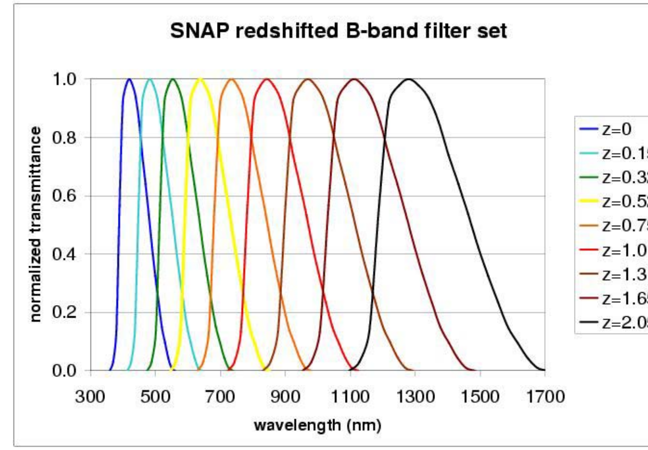
Guider NIR Visible Focus star projectors



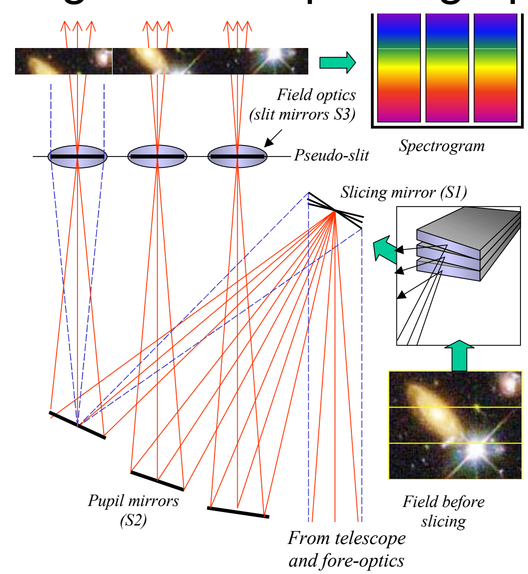
Spectrograph port

Calibration projectors

Fixed filters atop the sensors

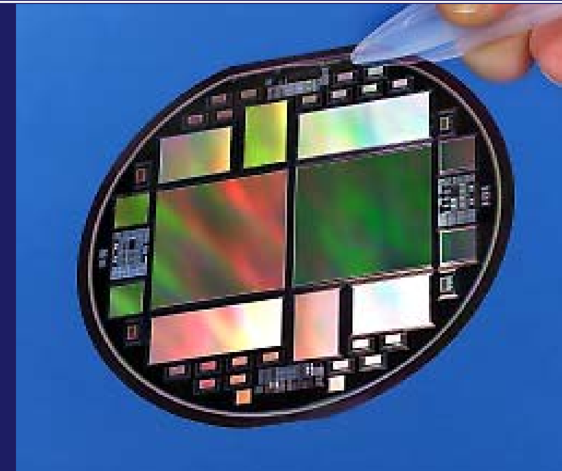


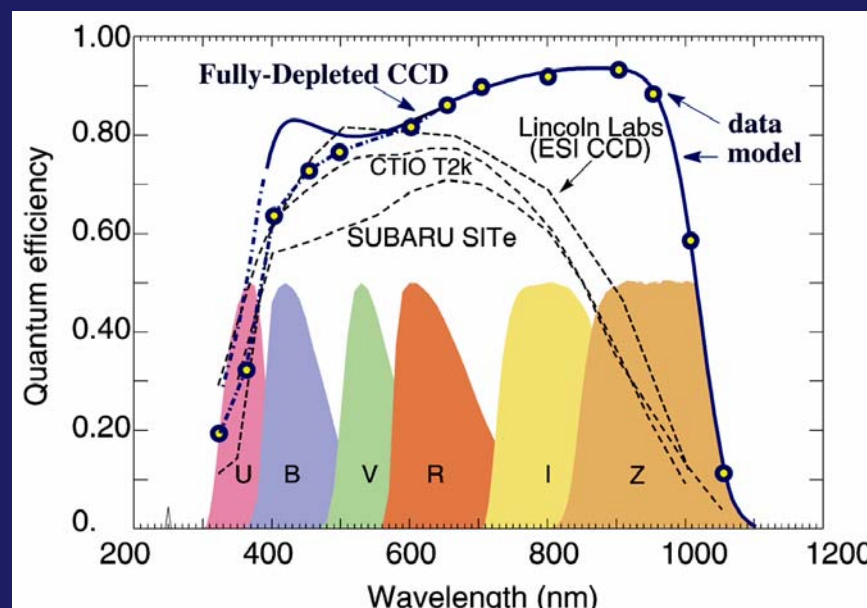
Integral Field Spectrograph



High-Resistivity CCDs for SNAP

- New kind of Charged Coupled Device (CCD) developed at LBNL.
- Better overall response than more costly "thinned" devices in use.
- High-purity "radiation detector" silicon has better radiation tolerance for space applications.
- The CCD's can be abutted on all four sides enabling very large mosaic arrays.

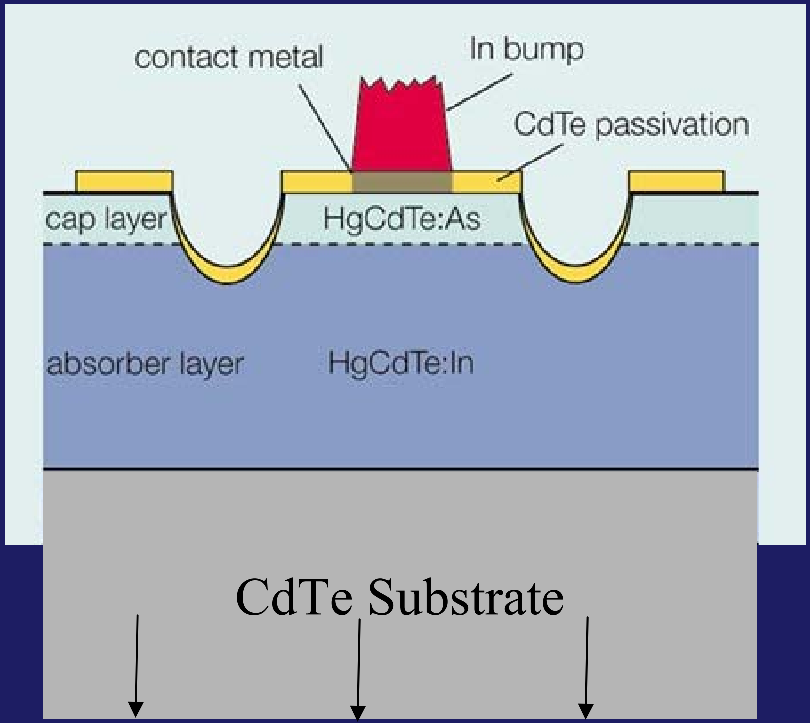


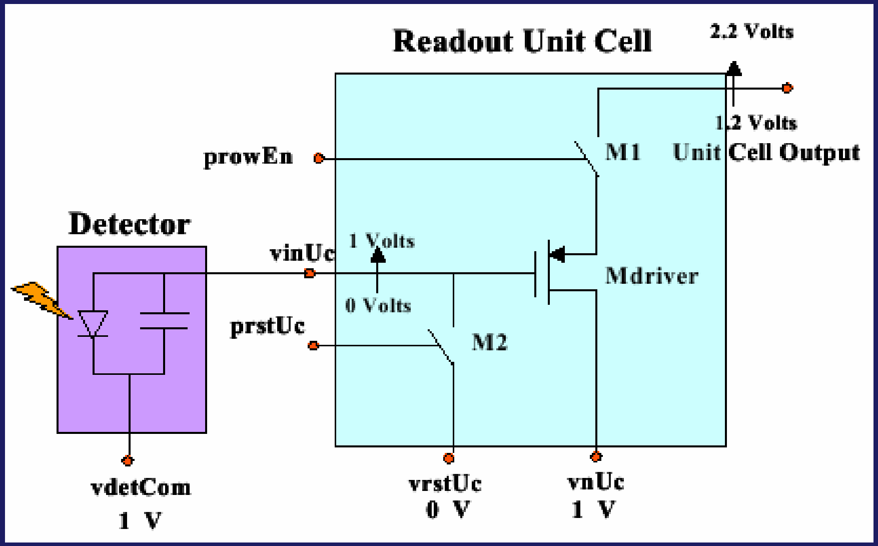


LBNL "Red Hots": NOAO September 2001 newsletter

Hybridized 1.7 μm cutoff HgCdTe Detectors

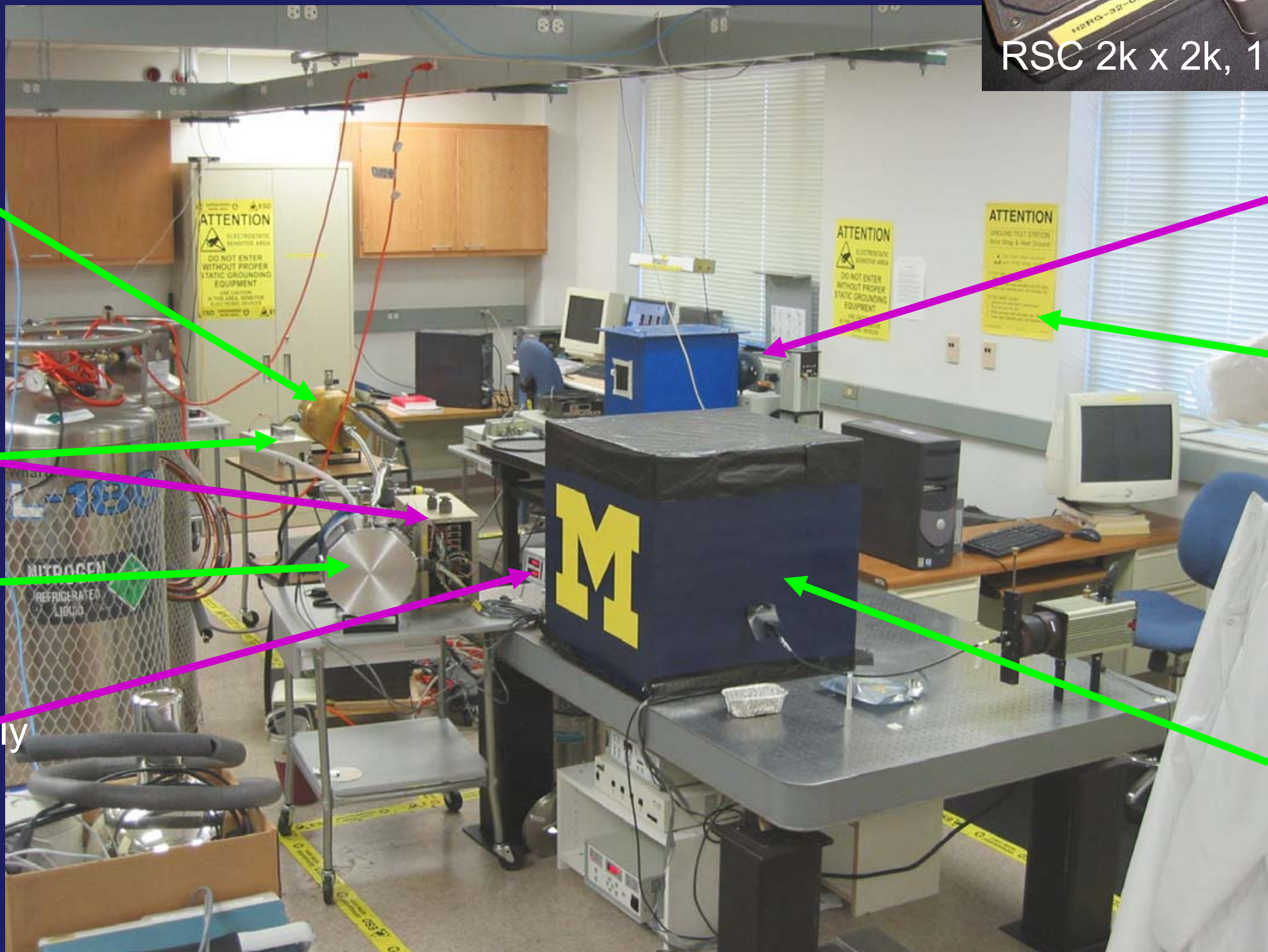
- Ongoing R&D effort with Rockwell Scientific and Raytheon Vision Systems to produce high QE, low noise 2Kx2K detectors
- CMOS readout bump bonded to HgCdTe diode
- Non-destructive readout – cosmic ray rejection, reduce read noise
- CdTe substrate will be removed – proton induced luminescence



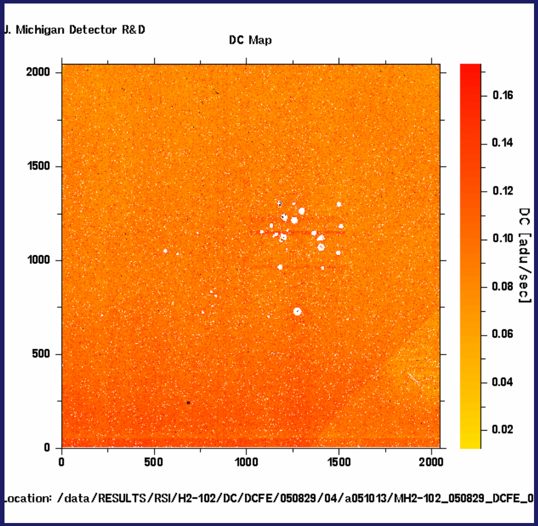


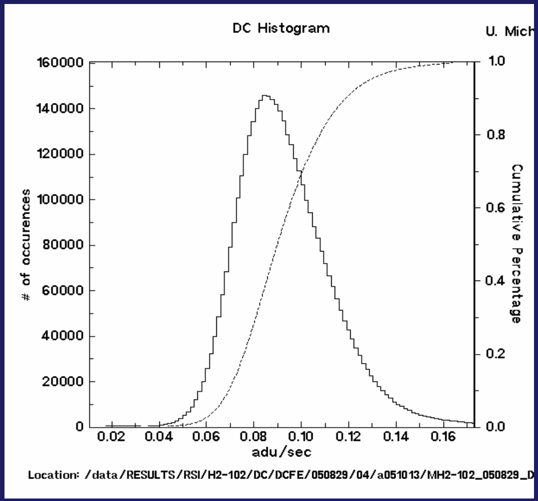
UM NIR Laboratory


RSC 2k x 2k, 1.7 μm HgCdTe

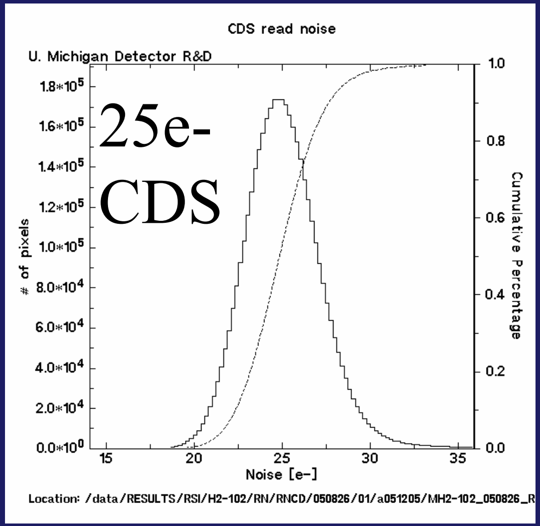


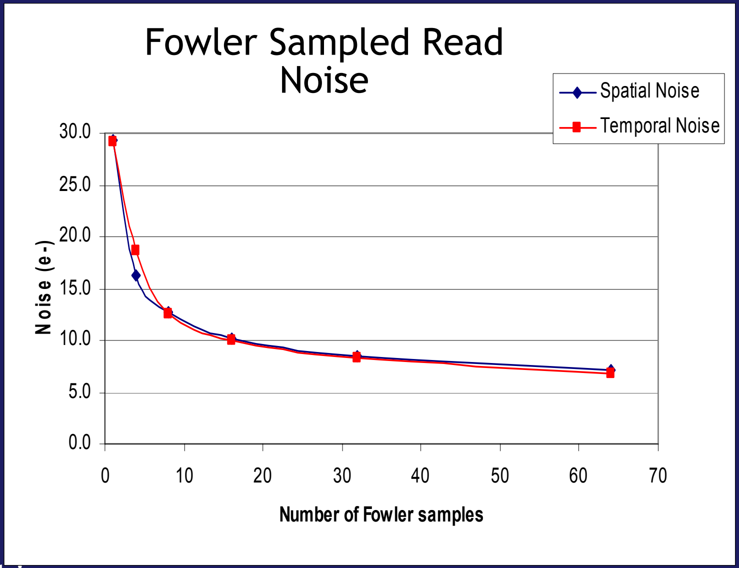
Dark Current, Noise and Multiple Sampling





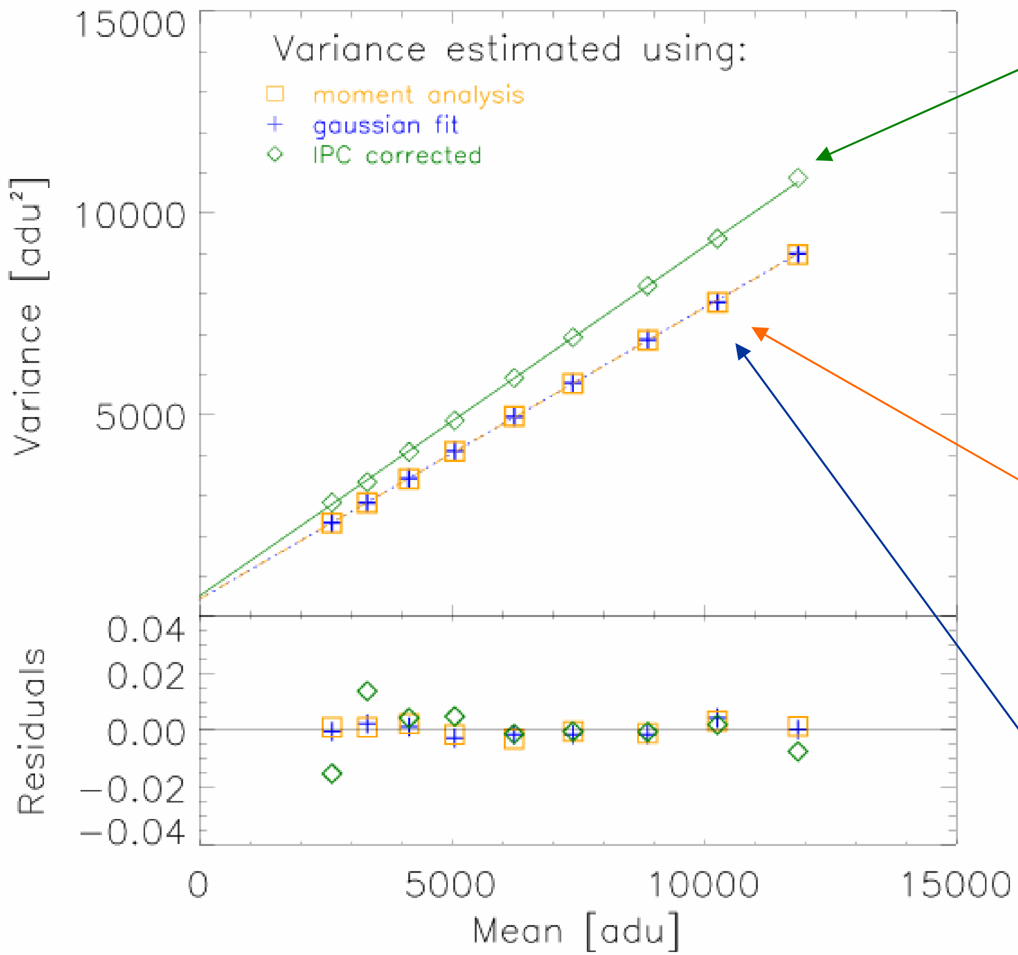
- Low dark current < 0.1e-/pixel/sec @ 140K (passively cooled focal plane temperature)
- Read Noise ~ 25e- dominates for 300s exposure
- Multiple sampling is used to reduce the read noise to < 10e-





Conversion Gain Measurement

Gain is measured with 3 techniques



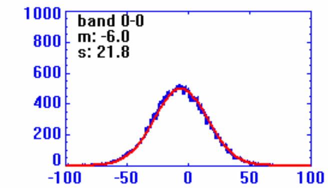
variance estimator accounts for IPC

$$\widehat{\sigma_D^2} = \frac{1}{2N}\left[\sum_{i,j} D^2[i,j] + 2\sum_{i,j} D[i,j]\,D[i+1,j] + 2\sum_{i,j} D[i,j]\,D[i,j+1]\right]$$

traditional variance estimator

$$\widehat{2\sigma_N^2} = \widehat{D^2} = \frac{\sum_{i,j} D^2[i,j]}{N}$$

standard gain measurement (Gaussian fit)



Ignoring correlated noise over-estimates the gain by ~ 20%. (for this device)

Agreement between **Gaussian** and **standard variance** methods confirms that outliers have been properly masked.

Capacitive Coupling - Autocorrelation

→ Cap. coupling occurs in mux and bump bond region

Average Correlation to neighboring pixels ~ 4%

(Nodal capacitance 32.2 fF 38.6 fF w/o IPC)

Average Correlation to neighboring pixels ~ 1% (rows), 0.5% (columns)

Nodal capacitance 75.1 fF

Average Correlation to neighboring pixels ~ 2.5% (rows), 1% (columns)

Nodal capacitance 77.7 fF

RSC Hawaii-2 HgCdTe with Epoxy Underfill

11	-3	0	-3	6	7	13
-7	14	4	23	-1	-9	-1
20	11	36	211	33	-4	-4
-3	12	265	5029	266	13	-3
-4	-5	34	210	37	9	22
0	-9	-1	22	7	14	-8
13	7	7	-3	1	-3	11

RVS HgCdTe before Epoxy Underfill

0	-6	-6	10	8	4	3
18	2	1	-2	-3	-8	6
0	-3	-1	20	4	9	0
6	2	50	4552	50	3	5
-1	7	3	20	0	-4	0
9	-6	-2	-3	3	2	14
5	5	6	7	-4	-6	-1

RVS HgCdTe after Epoxy Underfill

11	-5	-1	-6	0	3	-3
12	-13	3	11	2	-8	-13
3	-2	28	43	17	3	-5
10	13	113	4136	114	14	11
-4	2	16	42	28	-1	2
-13	-7	4	9	5	-12	12
0	5	0	-5	0	-3	7

trace topology in multiplexer

before

after

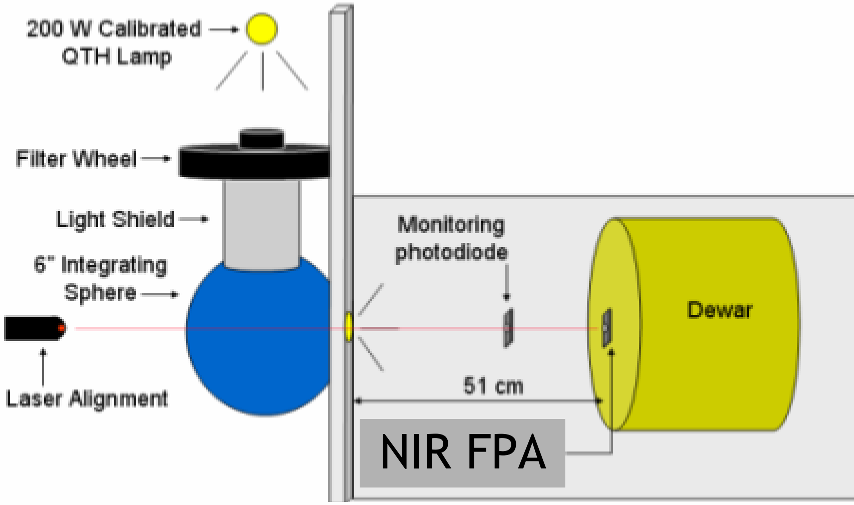
epoxy underfill

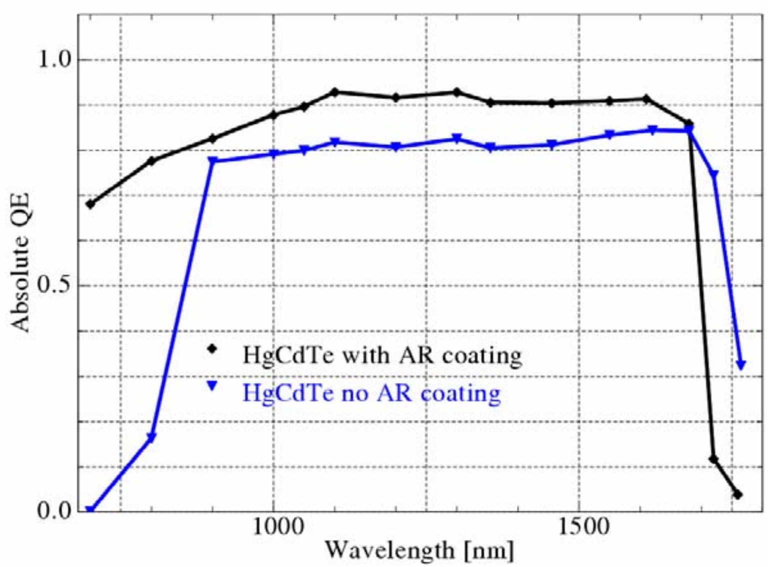
correlation increases by ~ 2x

MGB, M. Schubnell, & G. Tarle, "Correlated Noise and Gain in Unfilled and Epoxy Under-filled Hybridized HgCdTe Detectors," *Submitted to PASP*, Mar. 2006.

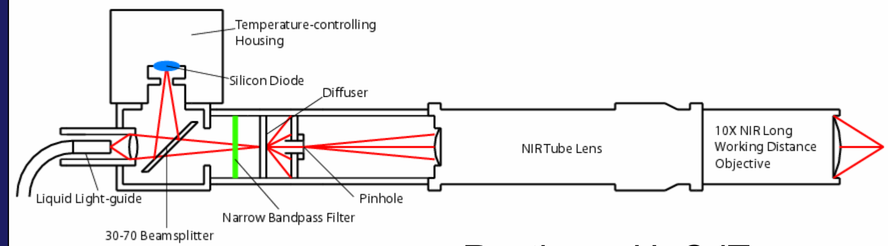
Precision NIR Photometry

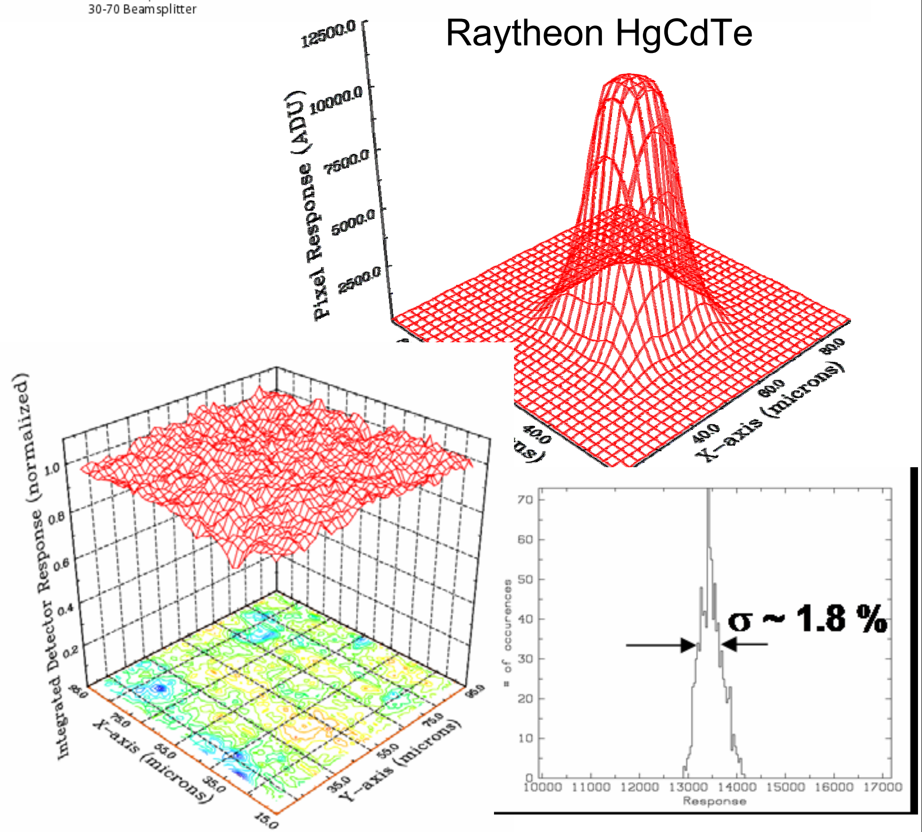
QE Measurement
(5% absolute achieved; 2% goal)



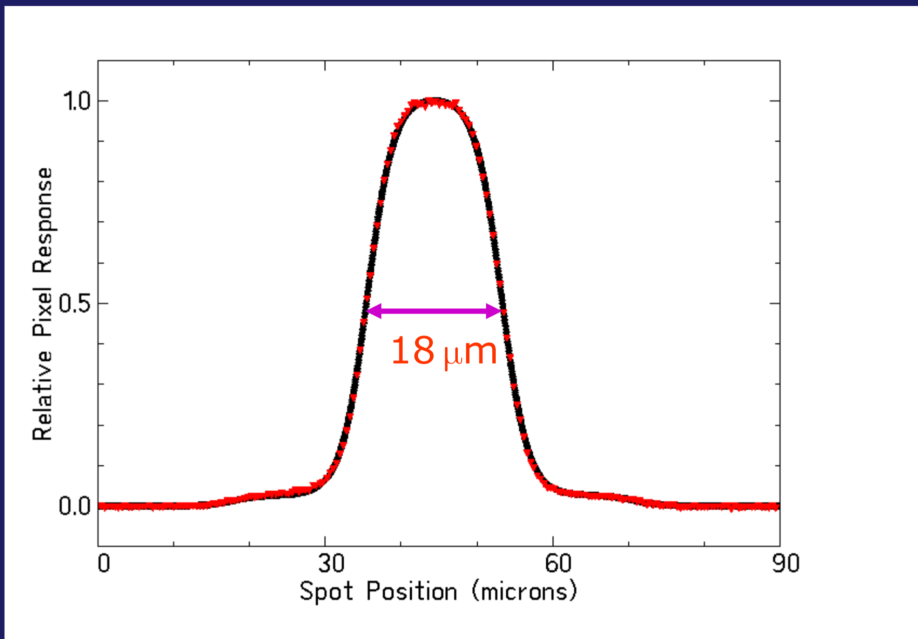


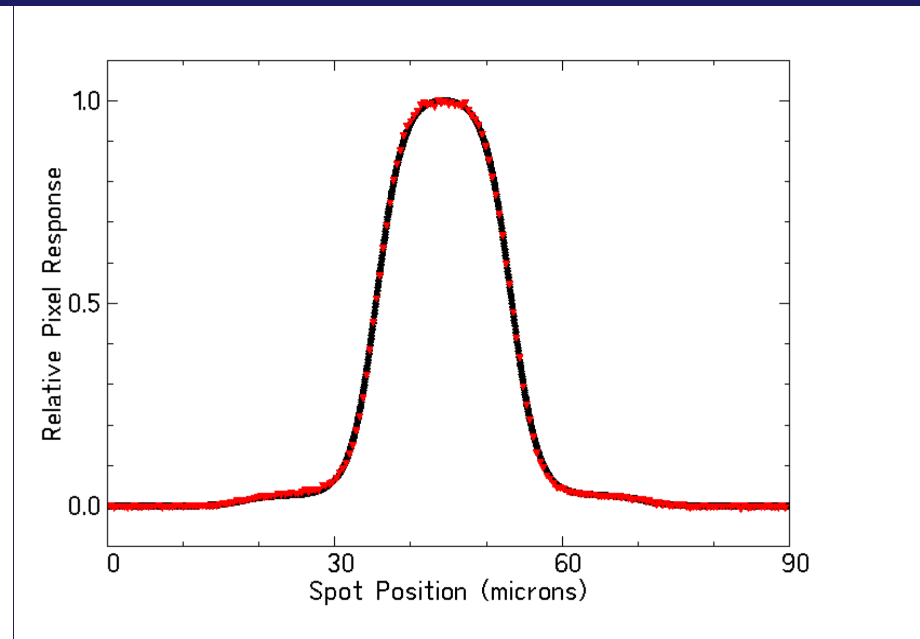
Micron-size NIR point projection system uncovers sub-pixel structure





"De-convolution" – Understanding Intra-pixel Response





start with square PRF (18 μm)

convolve with PSF (1.4 μm)

add charge diffusion (1.7±.02 μm)

add capacitive coupling (2.2 ±.1%)

compare to data

let's fit also the pixel width:

square PRF (17.8 ± .1 μm)

PSF (1.4 μm)

charge diffusion (1.7 ± .02 μm)

capacitive coupling (2.4 ± .1%)

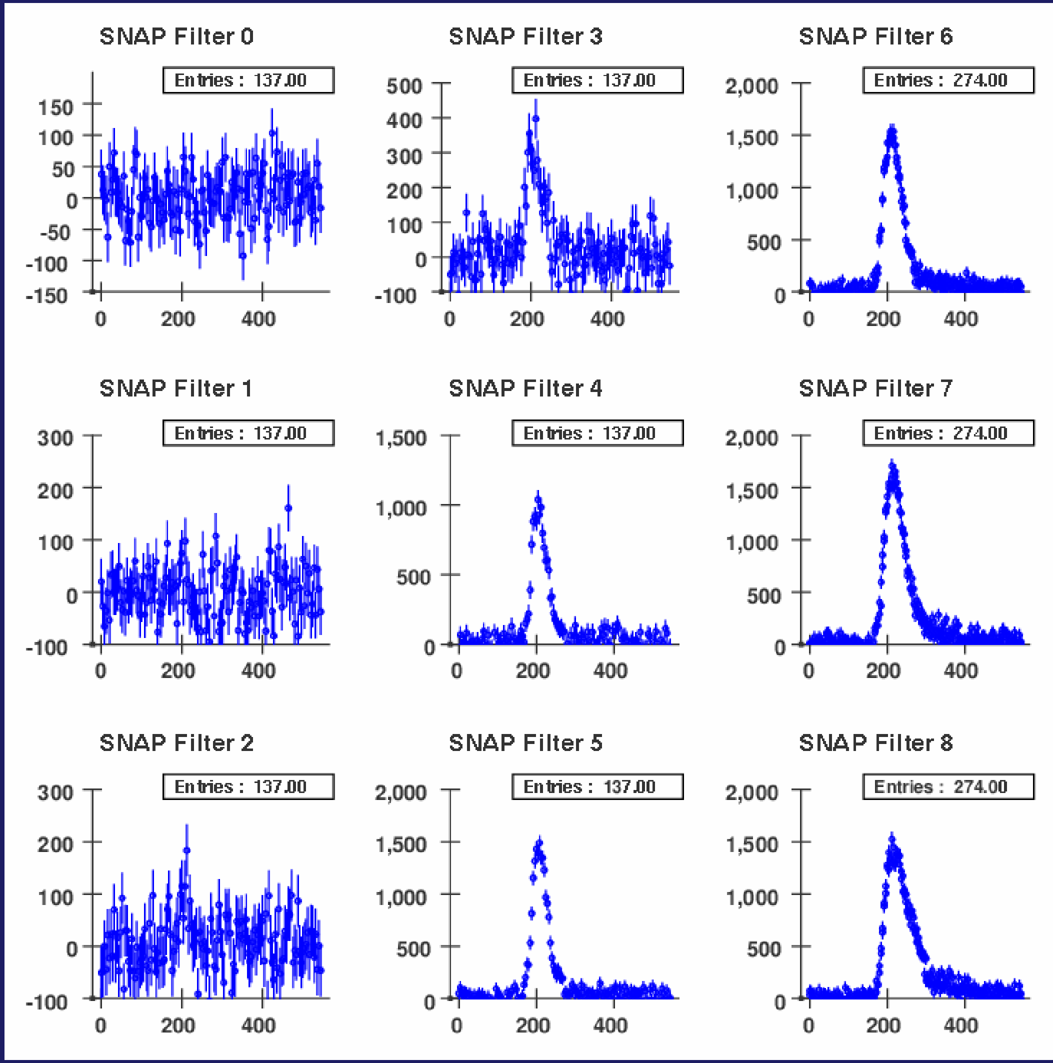
published value: 2.2 ± .1%

"Sub-pixel Response Measurements of Near-Infrared Sensors," *in preparation*

Simulations

Simulated Detector Performance

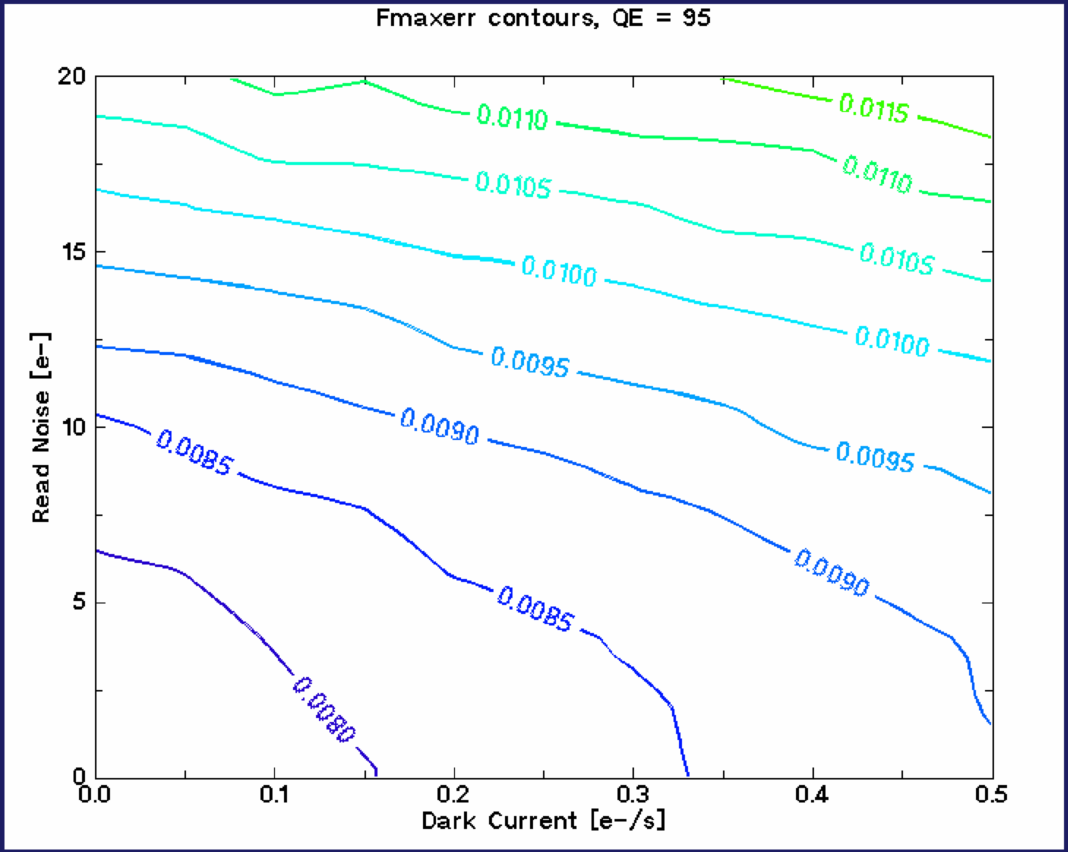
z = 1.7 supernova Ia



Detector parameters measured in the lab are used to simulate light curves

Simulated Detector Performance

z = 1.7 supernova Ia



% error on peak flux, QE = 95%

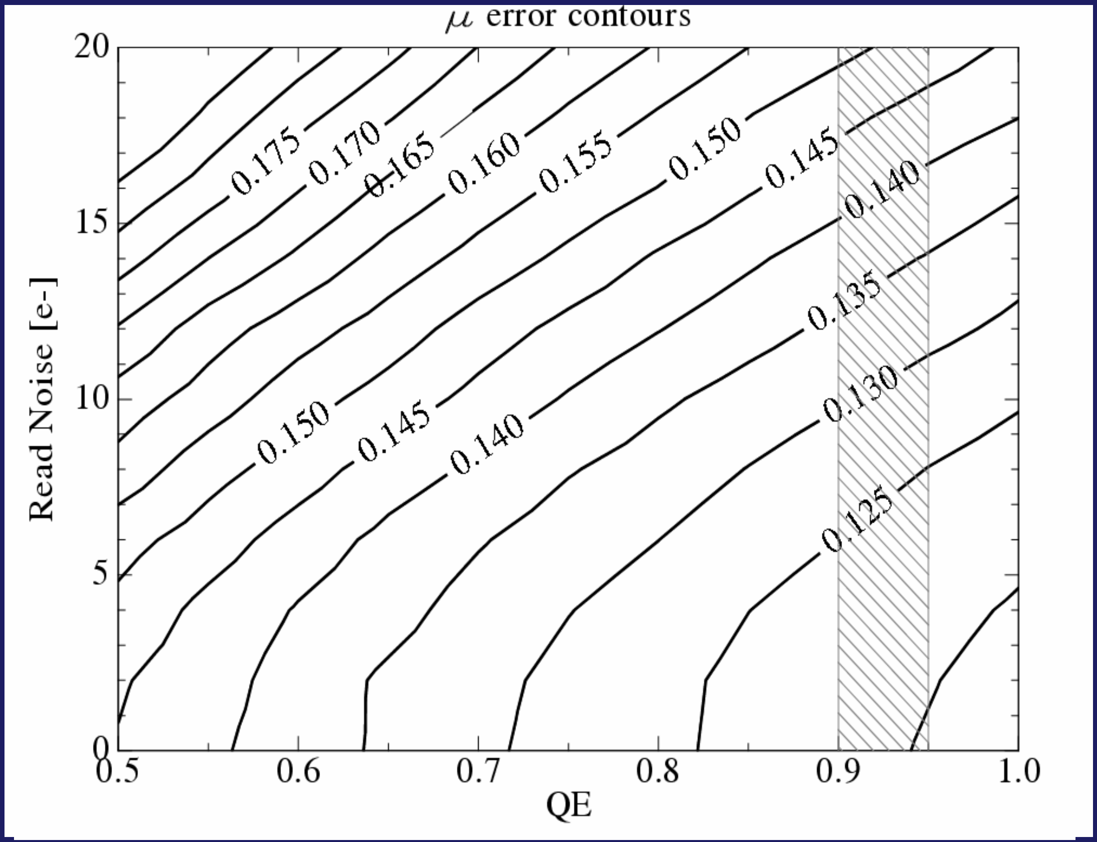
Detector parameters measured in the lab are used to simulate light curves

Light curve fits → parameter errors vs. detector noise

MGB et al., "Development of NIR Detectors and Science Driven Requirements for SNAP," *Proceedings of the SPIE*, Volume 6265, May 2006.

Simulated Detector Performance

z = 1.7 supernova Ia



Detector parameters measured in the lab are used to simulate light curves

Light curve fits → parameter errors vs. detector noise

Multi-band light curve fits → error on SNe peak magnitude

Magnitude error for z=1.7 SNe (type Ia dispersion 0.12-0.15 mag)

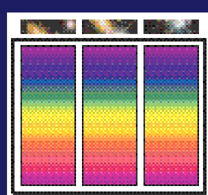
MGB et al., "Development of NIR Detectors and Science Driven Requirements for SNAP," *Proceedings of the SPIE*, Volume 6265, May 2006.

Data Sheets to Cosmological Parameters

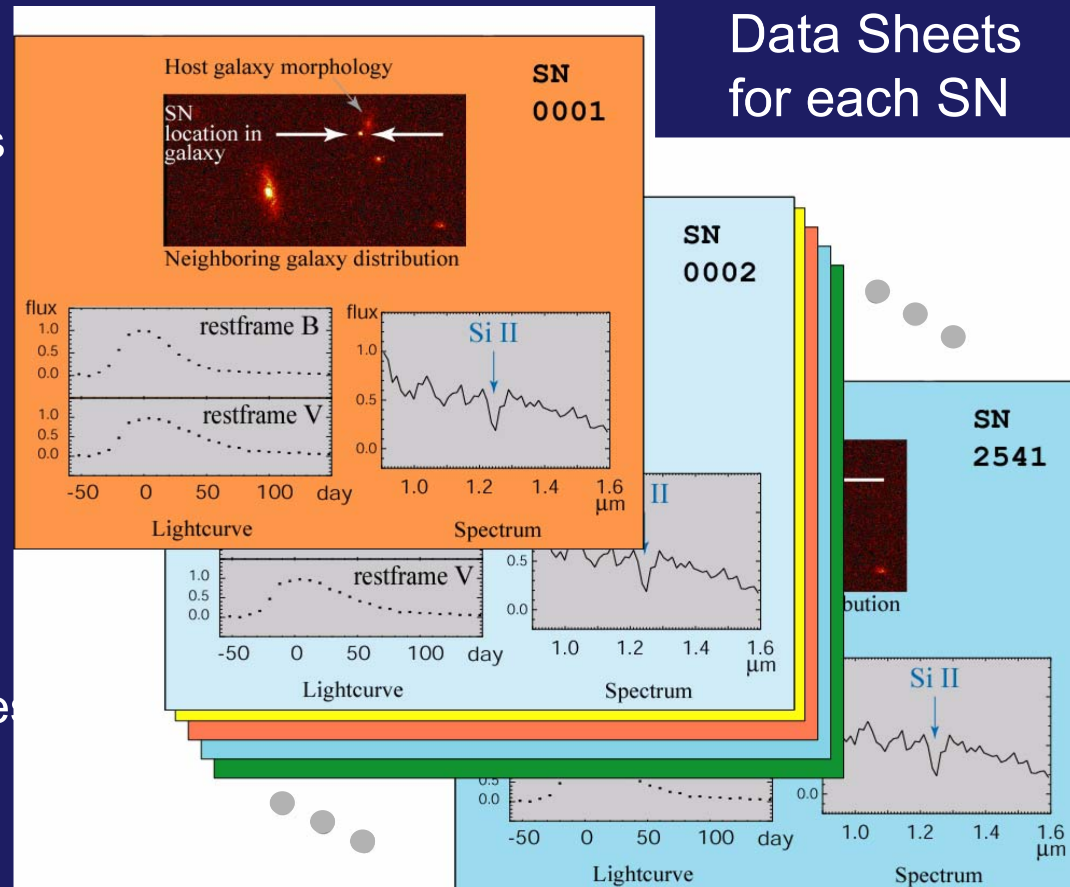
Images

Lightcurve &
Peak Brightness

Spectra



Redshift &
SN Properties

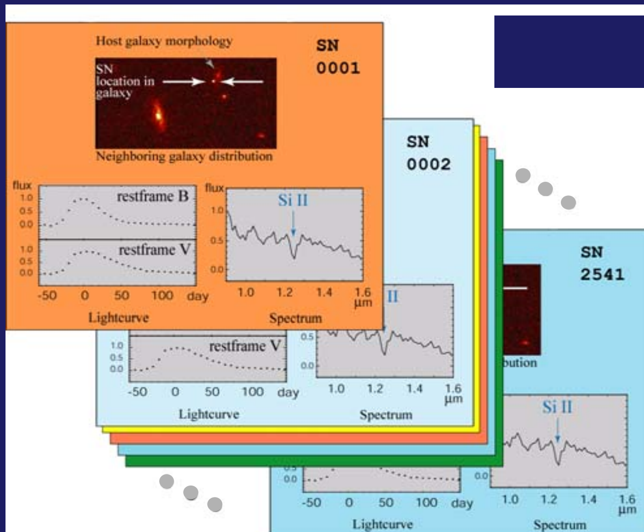


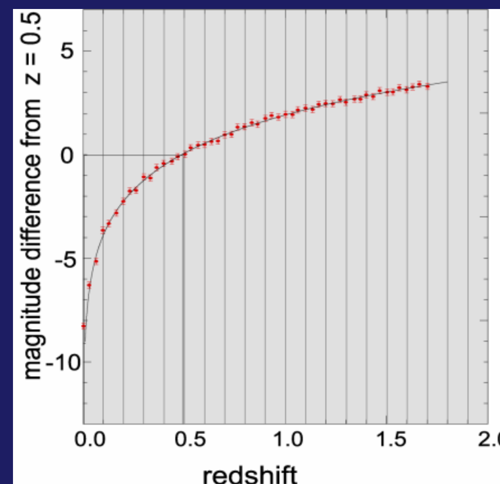
Data Sheets
for each SN

Instrument → Observed Data

Mission Plan

Data Sheets to Cosmological Parameters

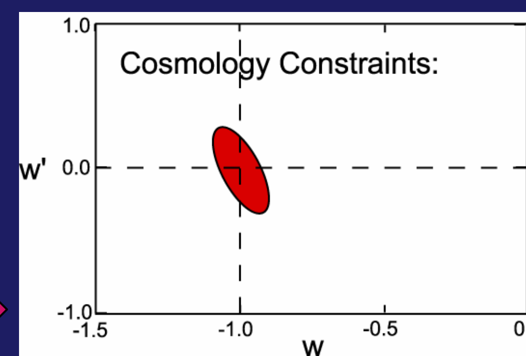




Ω_M and Ω_Λ

Dark Energy Properties

(w_0 and w')

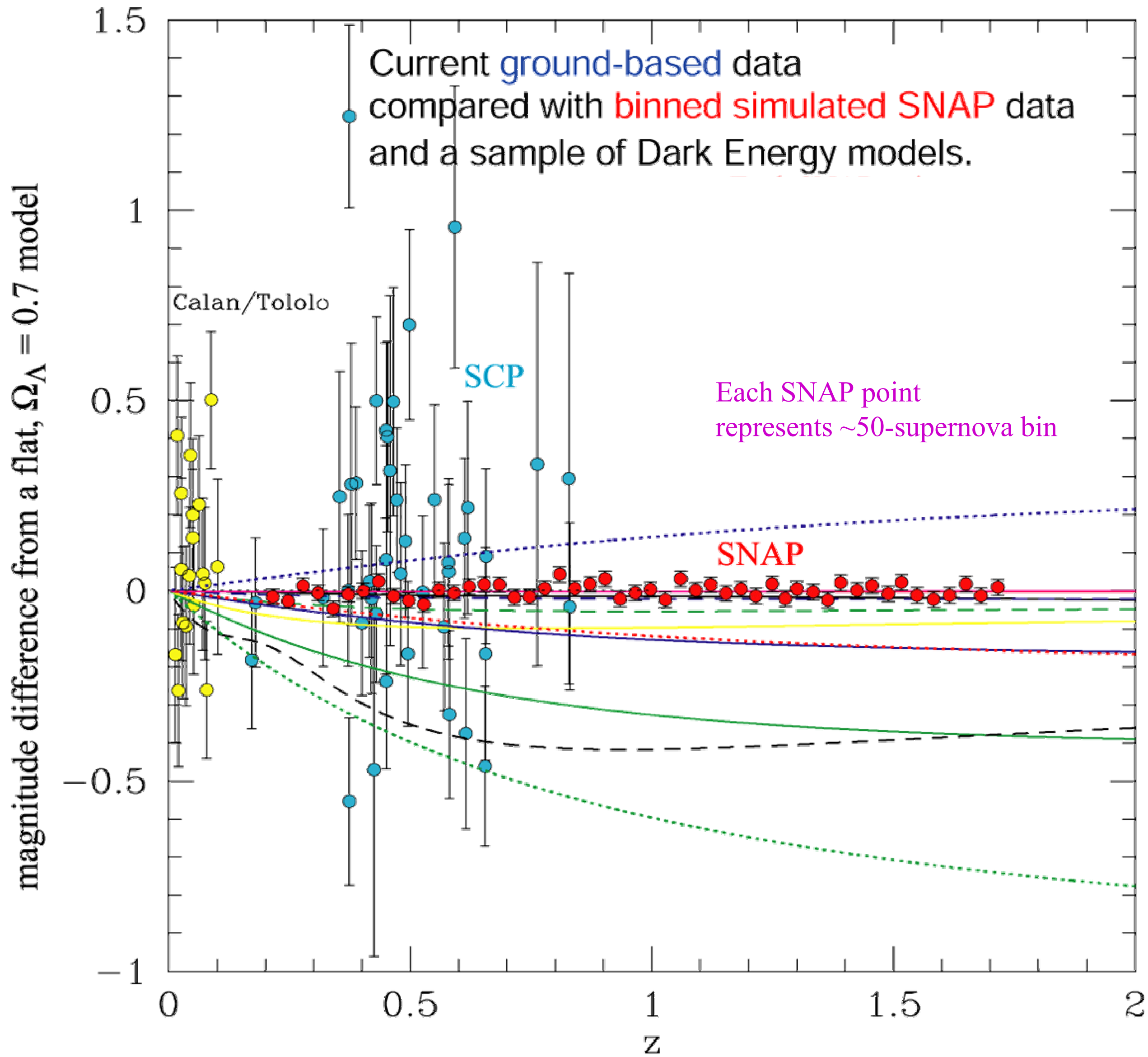


Data → Analysis → Physics

Calibration Plan, External SN Obs.

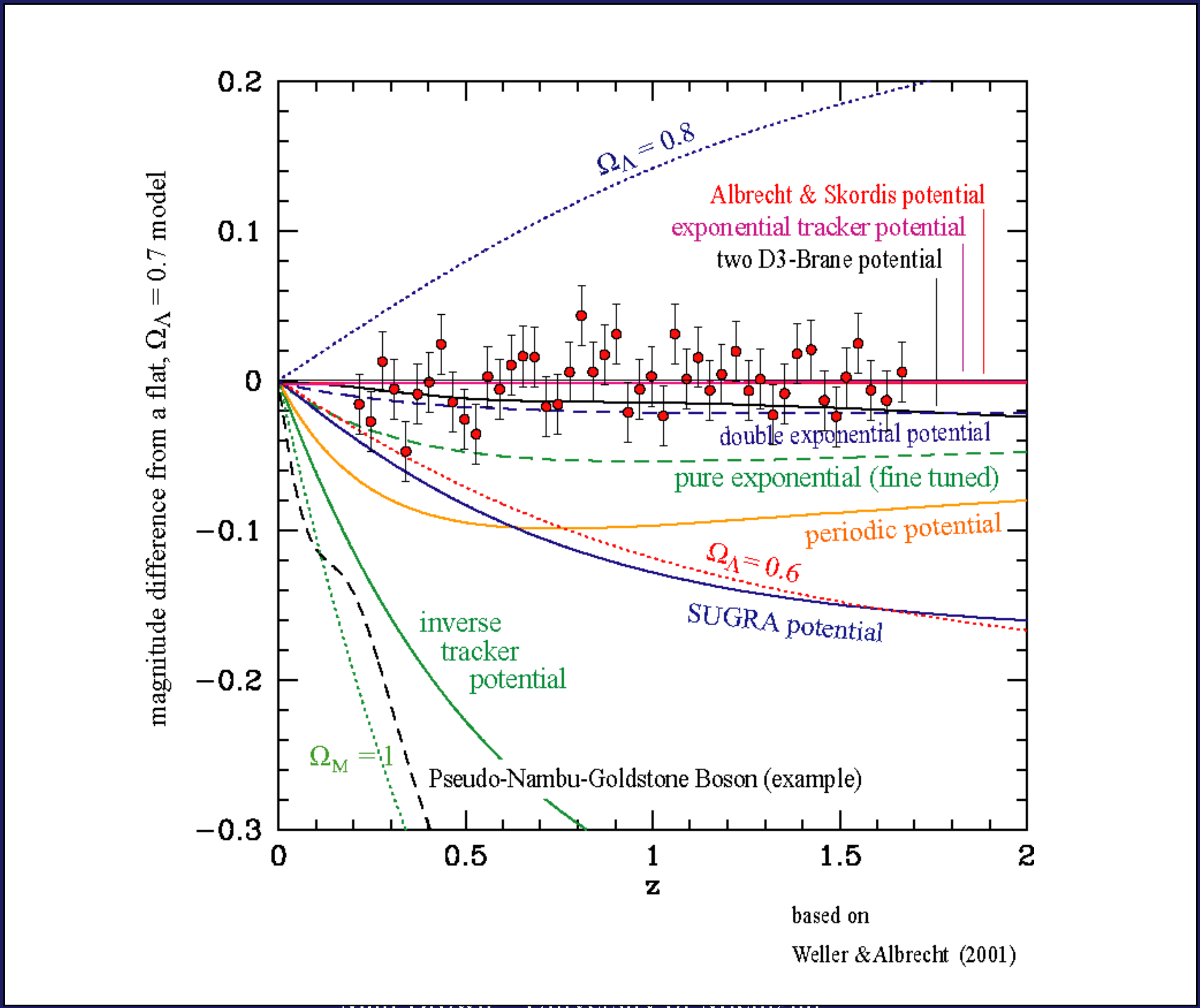
Priors, External Cosmology

Simulated SNAP data



based on
Weller & Albrecht (2001)

Understanding Dark Energy



Conclusions

Dark energy is the dominant fundamental constituent of our Universe, yet we know very little about it.

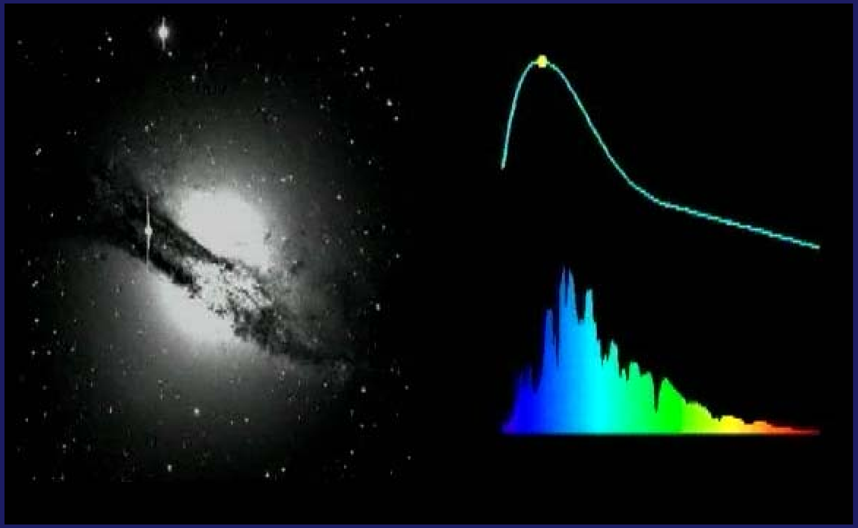
SNAP will test theories of dark energy and show how the expansion rate has varied over the history of the Universe.

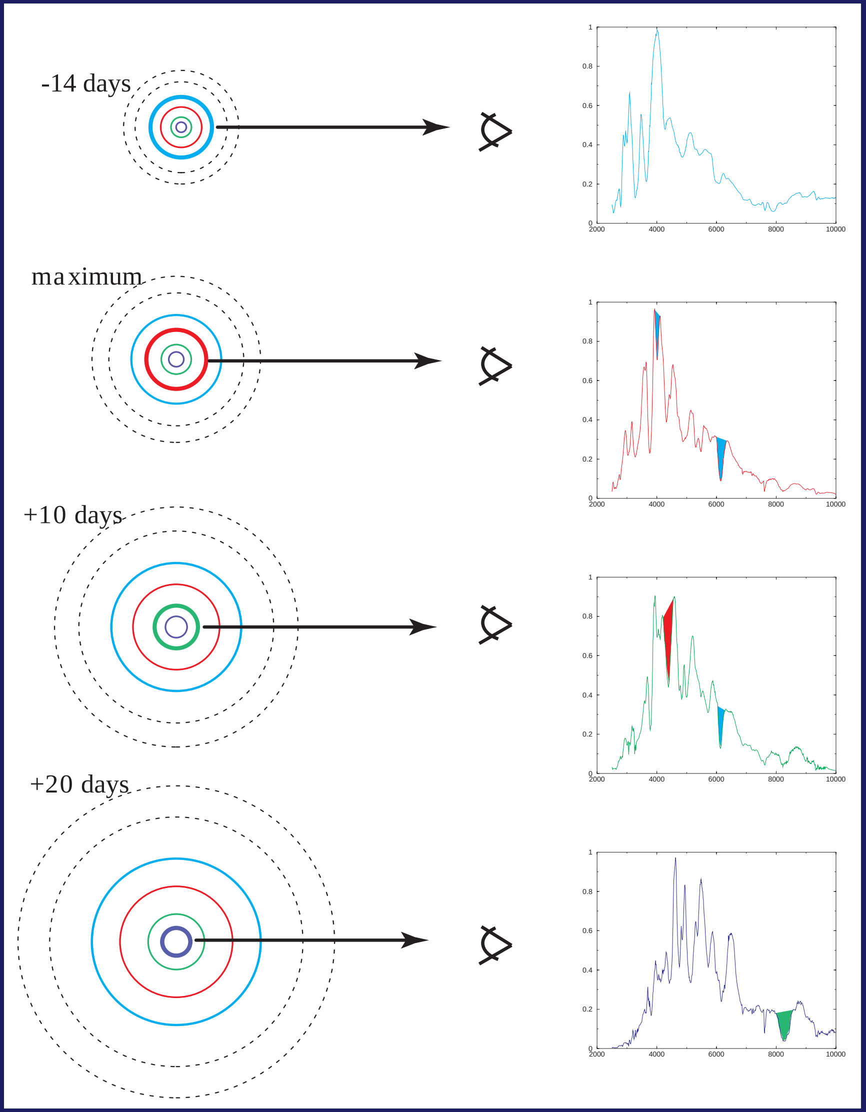
A vigorous R&D program, supported by the DoE is underway, leading to an expected launch early in the next decade.

THE END

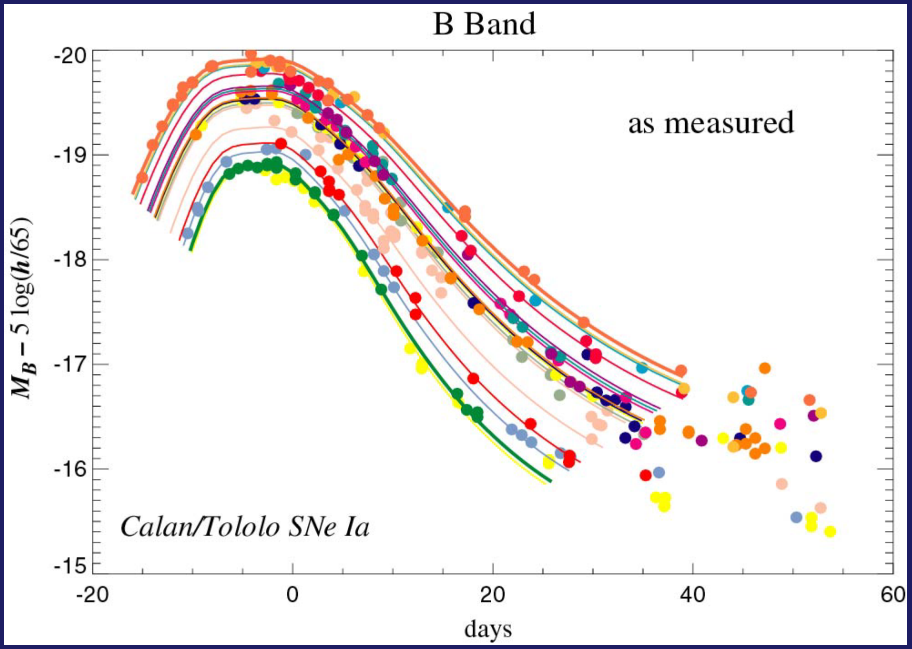
SN "Tomography"

At every moment in the explosion event, each individual supernova is sending a rich stream of information about its internal physical state





Calibrated Standard Candles

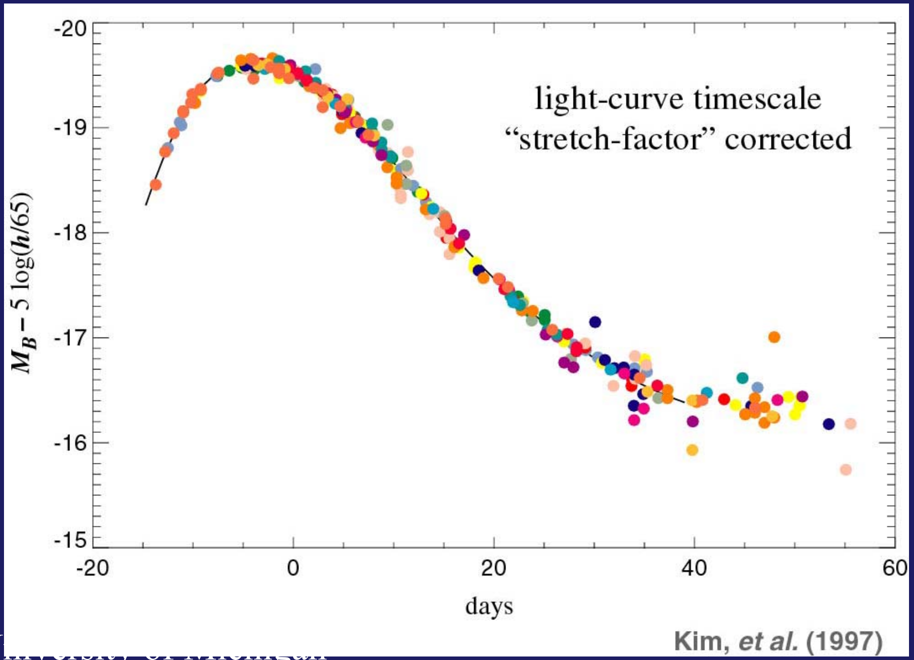


Brightness not quite standard, but correlated with light curve timescale

Intrinsically brighter SNe last longer.

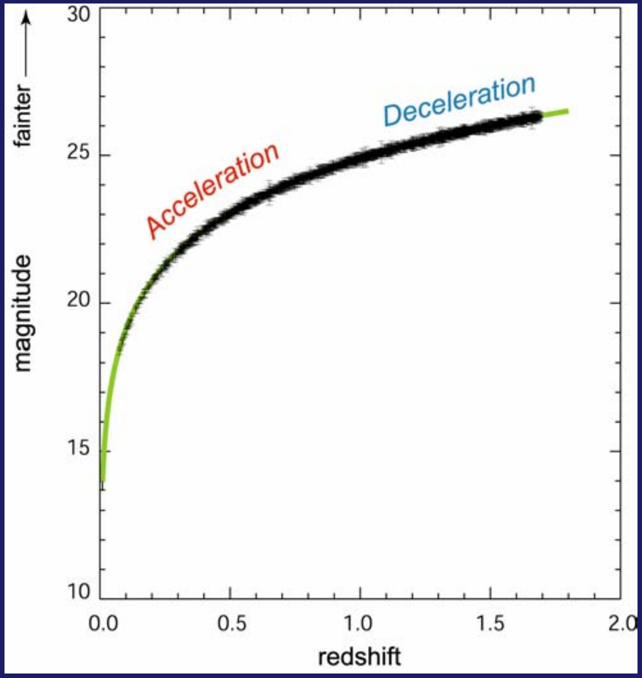
Peak-magnitude dispersion of 0.25 – 0.3 magnitudes

~0.15 magnitude dispersion



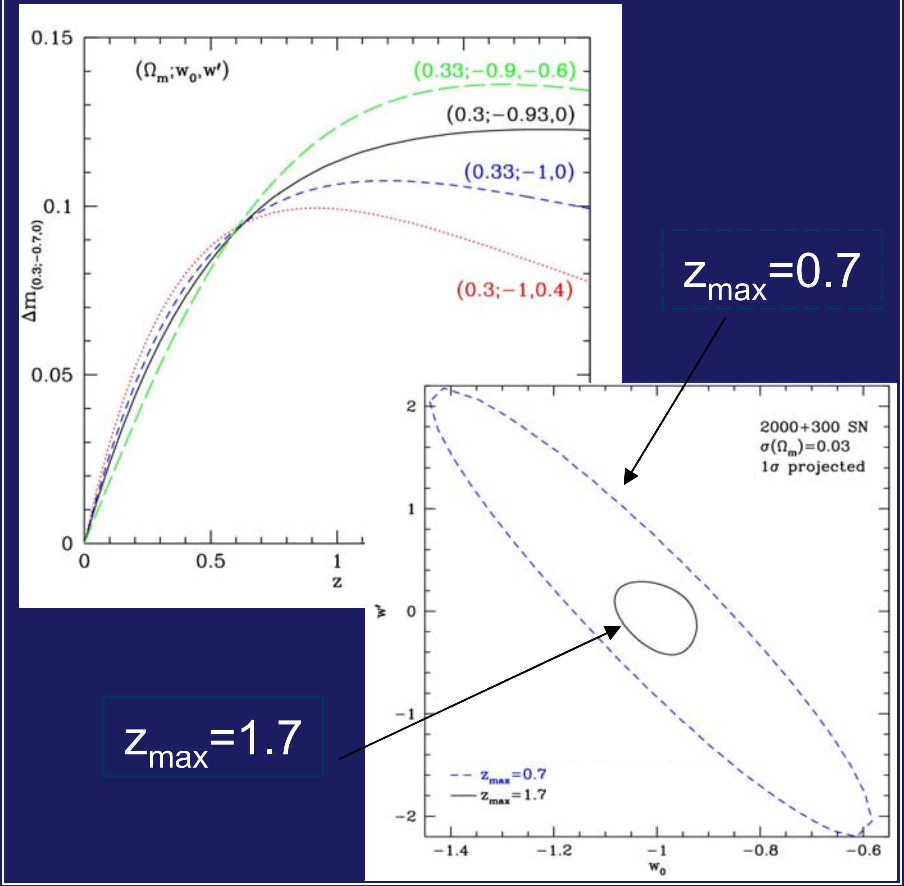
Why go to high redshifts?

- Dark energy can be detected at low redshift (SCP, High-z). To determine what it is, and not just that it is, requires measurements over both the acceleration and deceleration epochs.
- This long reach breaks essential degeneracies which low redshift data alone cannot.



SNAP will

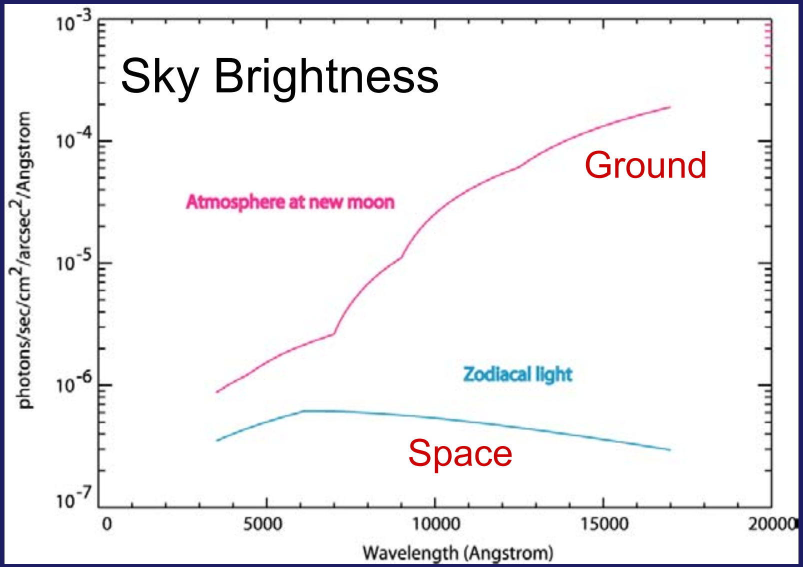
- ✓ probe the variability of w, providing an essential clue to the nature of DE.
- ✓ measure w_0 precisely to determine whether it is a cosmological constant.

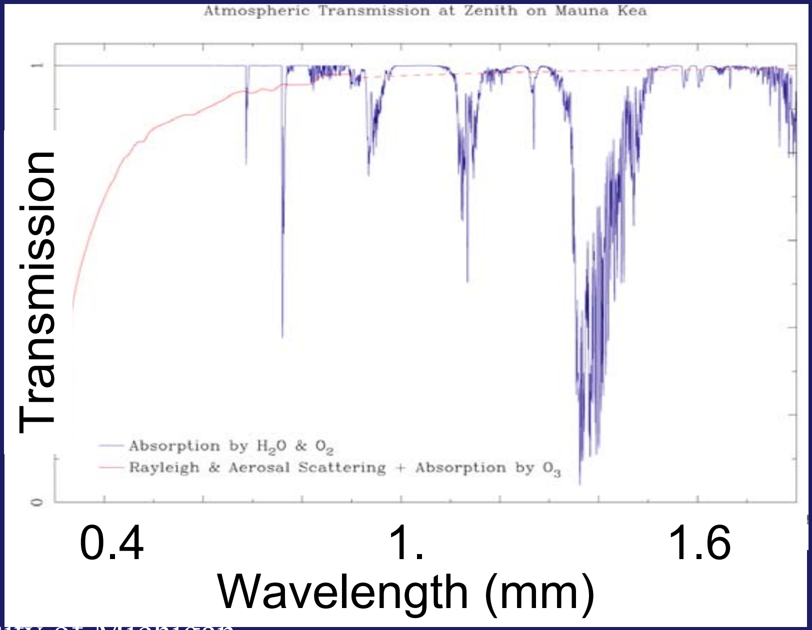


NIR available only in space

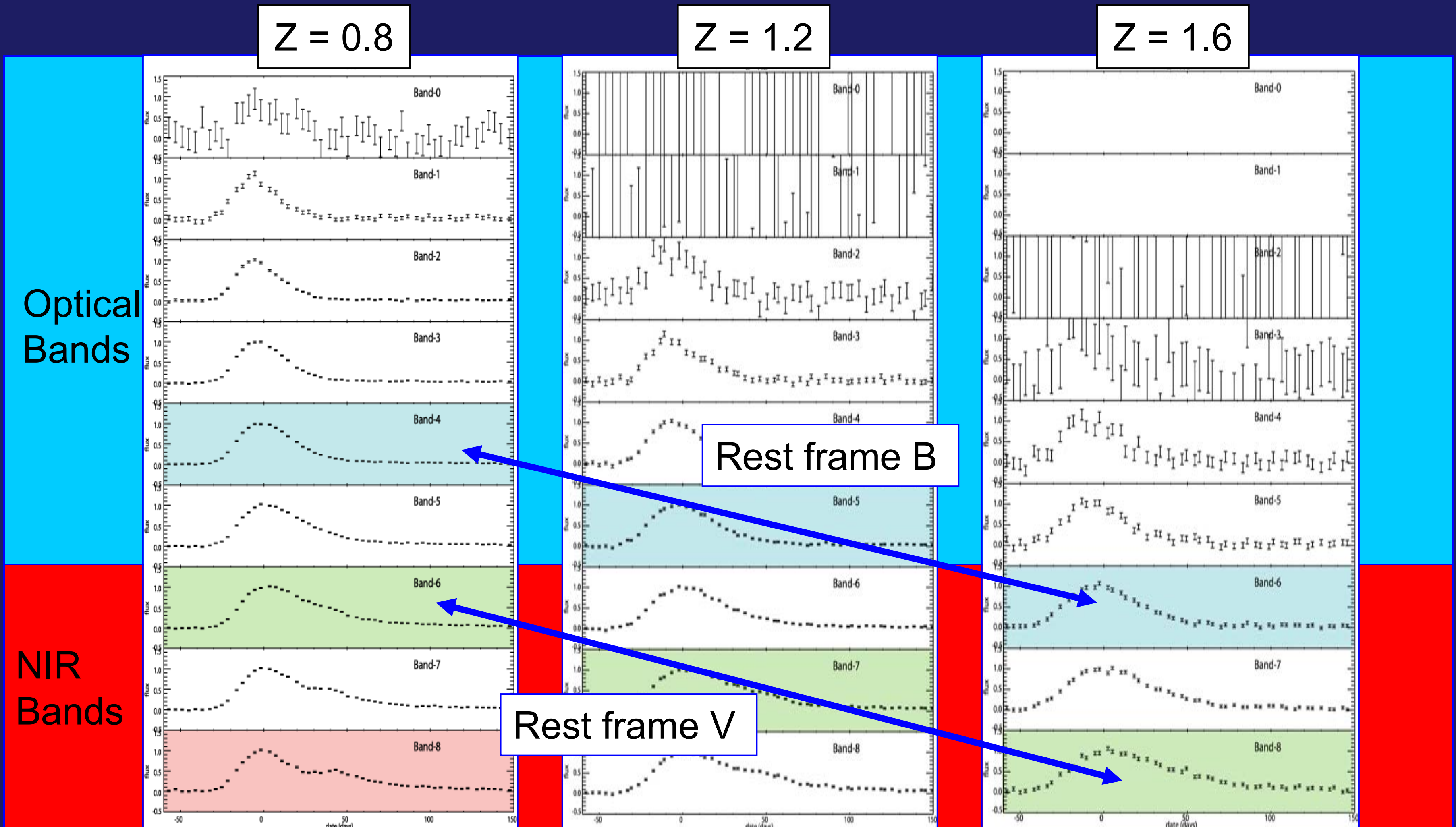
Crucial near-infrared observations are impossible from the ground

- Sky is very bright in NIR, about 500x brighter at 1.5μm, like observing the sky in Manhattan
- Sky is not transparent in NIR, absorption due to H_2O molecular absorption bands is very strong and extremely variable



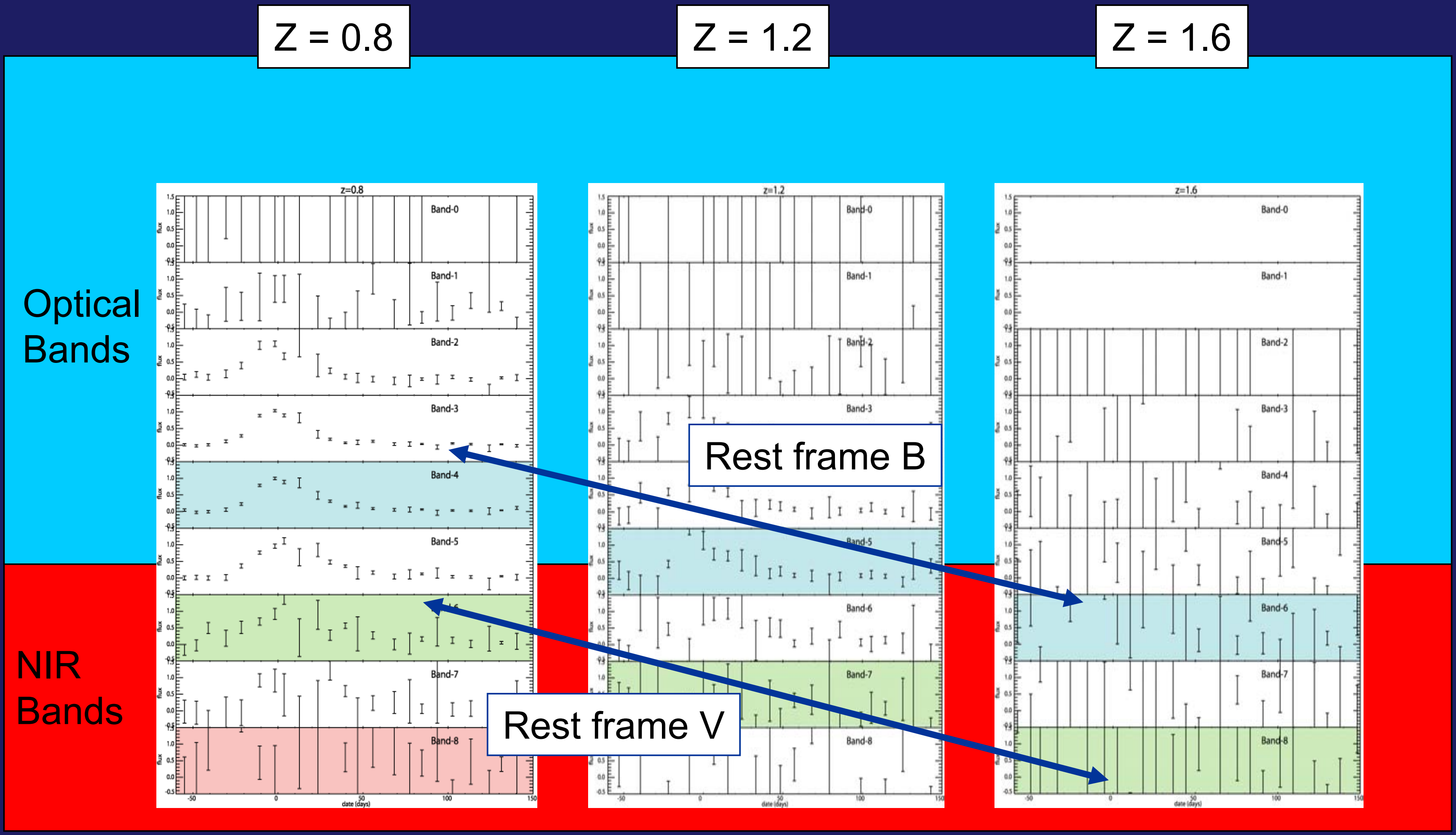


Rest frame B and V shift to NIR



Simulated SNAP observations of high redshift SNe

This can't be done on the ground!



Simulated 8m telescope ground based observations of high redshift SNe